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REPUBLIC OF SOUTH AFRICA

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the documents attached hereto, are true copies of  
Application Form P1, P2, Provisional Specification and  
drawings of Patent Application No. 2002/7439 filed in the  
names of **NORTON, Alan Eric, CRUNDWELL, Frank  
Kenneth** on the 17 September 2002 and the invention  
entitled: "HEAP LEACH PROCESS".

PCT IB 03 4186 .

Geteken te  
Signed at

PRETORIA

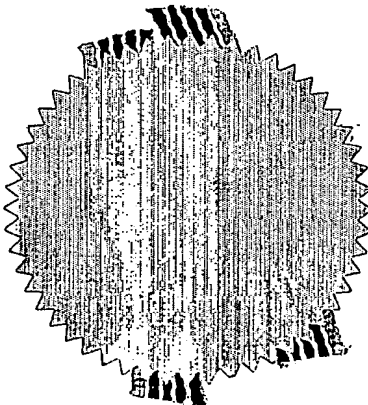
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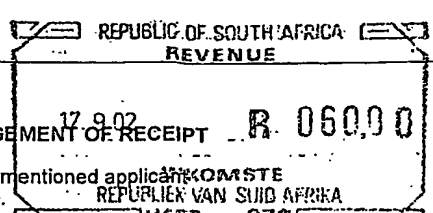
October 2003

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Registrateur van Patente



Form P.1

REPUBLIC OF SOUTH AFRICA  
PATENTS ACT, 1978

APPLICATION FOR A PATENT AND ACKNOWLEDGEMENT OF RECEIPT  
(Section 30 (1) - Regulation 22)

The grant of a patent is hereby requested by the undermentioned applicant on the basis of the present application filed in duplicate.

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| OFFICIAL APPLICATION NO |               |
| 21                      | 01 2002/ 7439 |

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| AGENT'S REFERENCE |
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|                              |  |
|------------------------------|--|
| FULL NAME(S) OF APPLICANT(S) |  |
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|  |                    |
|--|--------------------|
| TITLE OF INVENTION   |                    |
| 54   | HEAP LEACH PROCESS |
| THE APPLICANT CLAIMS PRIORITY AS SET OUT ON THE ACCOMPANYING FORM P2<br>The earliest priority claimed is |                    |
| THIS APPLICATION IS FOR A PATENT OF ADDITION TO PATENT APPLICATION NO.                                   |                    |
| 21   | 01                 |
| THIS APPLICATION IS FRESH APPLICATION IN TERMS OF SECTION 37 AND BASED ON APPLICATION NO.                |                    |
| 21   | 01                 |

|                                      |     |  |
|--------------------------------------|-----|--|
| THIS APPLICATION IS ACCOMPANIED BY : |     |  |
| X                                    | 1a  | A single copy of a provisional specification of 41 pages.                |
|                                      | 1b  | Two copies of a complete specification of pages.                         |
|                                      | 2a  | Informal drawings of sheets.   |
| X                                    | 2b  | Formal drawings of 19 sheets.  |
|                                      | 3   | Publication particulars and abstract (form P8 in duplicate).             |
|                                      | 4   | A copy of figure of the drawings for the abstract.                       |
|                                      | 5   | Assignment of invention (from the inventors) or other evidence of title. |
|                                      | 6   | Certified priority document(s).  |
|                                      | 7   | Translation of priority document(s).                                     |
|                                      | 8   | Assignment of priority rights.   |
|                                      | 9   | A copy of form P2 and a specification of S.A. Patent Application.        |
| X                                    | 10  | A declaration and power of attorney on form P3.                          |
|                                      | 11  | Request for ante-dating on form P4.                                      |
|                                      | 12  | Request for classification on form P9.                                   |
|                                      | 13a | Request for delay of acceptance on form P4.                              |
|                                      | 13b |  |

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DATED 17 September 2002

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| REGISTRAR OF PATENTS<br>REGISTRAR OF PATENTS<br>HANDELSMERKE EN OUTREKSTREG |

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| REPUBLIC OF SOUTH AFRICA  |  | PATENTS ACT, 1978                                  |                 |
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| FULL NAME(S) OF APPLICANT(S) / PATENTEE(S)                        |  |  |                 |
| 71  | NORTON, Alan Eric; CRUNDWELL, Frank Kenneth                          |  |                 |
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| 72  | NORTON, Alan Eric; CRUNDWELL, Frank Kenneth                          |  |                 |
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| 54  | HEAP LEACH PROCESS   |  |                 |
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## REPUBLIC OF SOUTH AFRICA

## PATENTS ACT, 1978

PROVISIONAL SPECIFICATION  
( Section 30 (1) - Regulation 27 )

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| 71                           | NORTON, Alan Eric; CRUNDWELL, Frank Kenneth |              |                   |                   |
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| 72                           | NORTON, Alan Eric; CRUNDWELL, Frank Kenneth |              |                   |                   |
| TITLE OF INVENTION           |   |              |                   |                   |
| 54                           | HEAP LEACH PROCESS                          |              |                   |                   |

P15256ZA00

## HEAP LEACHING PROCESS

### FIELD OF THE INVENTION

This invention relates to bio-assisted heap oxidation and leaching for the recovery of metals from ore.

### BACKGROUND TO THE INVENTION

Bio-assisted heap leaching for recovery of base metals is only carried out commercially on secondary copper sulphide ores. Recent work in Australia has seen the introduction of heap leaching for recovery of nickel from nickel sulphide ores on a semi-commercial test basis <sup>(1)</sup>. Bio-assisted heap oxidation of refractory gold ores is also used as a pre-treatment process for recovery of gold from such ores.

Typically the secondary copper sulphide heaps operate at temperatures in the range of 10°C to 25°C and rely on the exothermic oxidation of secondary copper sulphide minerals to keep the temperature of the heap above ambient conditions. The relatively low temperature limits the rate of sulphide mineral oxidation that

can be achieved. Additionally, chalcopyrite ores cannot be leached at these low temperatures because chalcopyrite is generally considered to be refractory to leaching at such temperatures.

An increase in the operating temperature of existing and new sulphide heap leach operations would significantly reduce leach times; ore and metal inventory, ultimate metal extraction and enable the leaching of copper from chalcopyrite ores.

It is well known that the mineral chalcopyrite can be leached satisfactorily at higher temperatures (between approximately 60°C and 90°C) using thermophilic microorganisms. Chalcopyrite bearing flotation concentrates (treated in stirred tank bioleach reactors) and chalcopyrite-bearing ores (treated in heap leach test columns) have both been successfully processed in the laboratory. Mintek claim a process whereby chalcopyrite concentrates can be bioleached using moderate thermophiles at around 45°C by a combination of ultra fine milling and redox control of the slurry as indicated in WO 01/31072 A1. The metal extraction from chalcopyrite ores achieved in simulated heap leaching, using laboratory columns, is dependent on the particle size of the ore, finer sizes generally increasing the amount of mineral that is accessible to the lixiviant. Commercial attempts to use bio-assisted heap leaching on chalcopyrite ores have failed (copper recoveries typically much less than 50% in long time periods ~1-10 years) primarily because of being unable to maintain the ore temperature at that required to satisfactorily leach chalcopyrite. Although chalcopyrite ores can be processed technically by crushing, milling, flotation of a concentrate and processing of the concentrate by a hydrometallurgical process or smelting, these steps are all relatively expensive and heap leaching would provide a more cost effective solution. Furthermore, many primary copper ores are too low in grade to be economic using conventional processes, but heap leaching may make them economically viable, thus opening many copper deposits to be treatable.

In addition to being able to treat chalcopyrite ores, higher temperatures in the heap leaching of base metals from sulphide ores would result in significantly higher leaching rates. In turn, leach pad area as well as ore and metal inventory would be greatly reduced giving substantial economic benefit. For example, a mine treating 15Mtpa ore with a grade of 1% copper and an overall copper recovery of 80% (producing 120ktpa copper) would typically have an area under leach of at least 1.5 million m<sup>2</sup>. Halving this area (by reducing the leach cycle by a factor of 2) would save US\$10-30 million on pad construction costs, as well as a similar amount via a reduction in working capital. Higher temperatures are also likely to increase the ultimate amount of metal extracted from the ore (compared to operating at a lower temperature) and ultimate metal extraction is perhaps generally one of the most important factors effecting economic performance. In the previous example an extraction increase of just 5% increases the project NPV, at a 10% discount rate, by about US\$60 million. Additionally at higher temperatures pyrite will be oxidised and generate sulphuric acid, reducing the amount of fresh sulphuric acid added into the ore. A reduction in acid consumption of 1kg/t ore, with an acid price of US\$50/t in the example would yield savings of US\$0.75 million per annum.

Chalcopyrite ores may contain other sulphide minerals in addition to chalcopyrite, for example covellite, chalcocite, bornite, enargite and pyrite. The oxidation of these sulphide minerals is exothermic in nature; on average sulphide minerals have a calorific value of around 25000kJ/kg of sulphide. The rate of oxidation of these minerals determines how quickly this energy is released. If we consider 1000m<sup>3</sup> of ore with a bulk density of 1.7t/m<sup>3</sup>, the ore mass is 1700t. Consider, as an example, that the ore contains 2% sulphide in the form of sulphide minerals. If the sulphides are fully oxidised over a period of 183 days, then the energy (1700t x 1000kg x 2% sulphide x 25000kJ/kg = 850GJ or 236MWh) is released over a period of 4368 hours. In this example the power generation represents ~54W/m<sup>3</sup> and can be likened to an electric light bulb, uniformly distributing ~54W within each cubic meter of the ore heap. Furthermore the energy required to

heat the rock (ignoring for the moment any moisture and air within the heap), with a specific heat of  $\sim 1000 \text{ J/kg}^\circ\text{C}$  from ambient (say  $20^\circ\text{C}$ ) to the operating temperature (say  $60^\circ\text{C}$ ) is  $1700 \text{ t} \times 1000 \text{ kg} \times \sim 1000 \text{ J/kg}^\circ\text{C} \times (60^\circ\text{C} - 20^\circ\text{C}) = 68 \text{ GJ}$ ; this energy is far less than that which is released during the oxidation reaction. Superficially, therefore, the energy released during the oxidation process is more than adequate to heat up the heap. In reality of course the moisture within the heap, as well as any air, has also to be heated, but this requirement is quite small compared to the requirement for the ore.

However there are several problems with this simplistic approach. There are various heat losses to take into account. In the case of base metals, for example copper, bio-assisted heap leaching requires the removal of dissolved copper and the ore heap is typically irrigated with an acidic lixiviant (usually solvent extraction raffinate) containing at least some iron in solution. The incoming irrigation solution will always be cooler than a satisfactorily operating heap and absorb energy (released in the exothermic oxidation process) as it passes down the heap, increasing in temperature as it does so. Bio-assisted heap leaching also requires air to be blown through the heap to provide oxygen for the oxidation reactions. In typical Chilean conditions, for example, the ambient air will be cold and contain a small amount of moisture. As the air enters the heap it meets the hot solution and cools the solution down transferring energy to the gas phase, which becomes warmer and more humid as it continues to rise, passing counter-current to the solution, until it meets the cooler regions at the top of the heap, where it cools down and water is condensed from the air. Additionally there will be some heating (during daylight) and cooling (during the night) of the heap surface, as well as cooling due to surface evaporation and radiative emission. At the same time the sulphides in the rock are generating heat of reaction; a complex system that will nevertheless reach a dynamic operating temperature profile throughout the depth of the heap. There will be very minor losses from the sides and bottom of the heap as well. Surface heat losses (as well as water



to evaporation) can be reduced by partially covering the heap with an insulating layer. Plastic sheeting has been used recently in industrial operations.

The air is provided on commercial operations by blowing air through a network of perforated pipes beneath the heap. However the air has another important role, over and above the provision of oxygen for the oxidation reactions, which is the movement of heat up or down within the heap.

Dixon gives a good account of the overall heap system <sup>(2)</sup>. Of particular note in Dixon's findings was the importance of the aeration mass flow  $G_a$ , relative to the solution irrigation mass flow  $G_i$  in kg per m<sup>2</sup> per hour and litre per m<sup>2</sup> per hour respectively. In the system considered by Dixon, there was a ratio of the aeration rate to the irrigation rate, that is to say  $G_a/G_i$ , which produced the highest heap average temperature, which Dixon found to be ~38°C. Slightly below this ratio, the average heap temperature fell off. Dixon found the critical  $G_a/G_i$  level was 0.35.

Dixon explained the net heat movement effect by the "combined advection coefficient". The solution moves heat downwards and moist warm air moves it upwards. If the combined advection coefficient is negative, the net heat transfer direction will be downwards with heat being removed via the PLS and the average heap temperature will reduce. If the combined advection coefficient is positive the net heat transfer will be towards the top of the heap, raising the average heap temperature. If the combined advection coefficient is too high, however, heat will be blown out of the top of the heap in the form of warm humid air, again reducing the average heap temperature.

Dixon concluded that increasing the temperature within a heap could be achieved by:

- Decreasing the solution irrigation rate

- o Higher rates of irrigation results in washing of heat out to the PLS, to the detriment of heap temperature.
- Increasing the aeration rate
  - o The aeration rates in typical industrial operations are insufficient to move heat upwards; consequently heat is lost to the irrigation solution as it exits the heap. Increasing the aeration rate can push heat upwards into the heap, significantly increasing average heap temperature. Increasing aeration rates was one of Dixon's major recommendations.
- Applying an evaporation shield to the heap surface
  - o An evaporation shield will reduce the effective surface heat transfer coefficient and resulting heat losses, increasing the average heap temperature. Recent industrial practice has seen heaps being covered with plastic sheeting.
- Heating the irrigation solution
  - o Due to the day/night cycle and evaporative cooling at the top of the heap, Dixon found that heating the irrigation solution from 10 to 30°C only increased the average heap temperature by about 3°C, in the best case (which was co-incident with operating the heap sub-optimally) and barely had any effect at all when operating the heap at a more favourable  $G_a/G_i$  ratio. Covering the heap with plastic sheeting only mitigates this effect to a small extent.
- Heating the air with and without humidification.
  - o Heating air without humidifying it has little effect because of the low heat capacity of dry air. Humidifying and heating the air significantly increases heap temperature, but at the cost of applying external energy.

In this specification the term "take-off point" means a temperature, achieved within a commercially viable time period, at which irrigation and aeration can

thereafter be applied in an optimal manner during the remainder of the leaching cycle.

### **OBJECT OF THE INVENTION**

It is an object of this invention to provide a heap leaching process that at least partly alleviates some of the abovementioned problems.

### **SUMMARY OF THE INVENTION**

In accordance with this invention there is provided a method of controlling a bio-assisted heap leaching process by maintaining an optimum heap temperature through varying aeration and irrigation rates of the heap as a function of at least one of a determination of the oxygen content of the gas phase within the heap and a determination of the temperature of the heap.

There is also provided a method of controlling a bio-assisted heap leaching process by maintaining an optimum heap temperature through varying aeration and irrigation rates of the heap as a function of at least one of a determination within, above or exiting the heap, of the wet bulb temperature of the gas phase, dry bulb temperature of the gas phase, solution redox, solution oxygen content, solution metal content, specifically recovered metal content, solution temperature, specifically the solution temperature exiting the heap, oxygen uptake rate and carbon dioxide uptake rate.

There is also provided for the method to include maintaining the ratio between the aeration rate and irrigation rate at an optimum value through varying at least one of the aeration and irrigation rates of the heap.

There is further provided for the optimum ratio value to be determined according to at least one of the oxidation rate of minerals within the heap, the height of the heap and the oxygen utilization within the heap.

There is also provided for a heap to be divided in zones, for an optimum ratio value to be determined for each zone, and for the optimum ratio for each zone to be determined according to at least one of the oxidation rate of minerals within each zone, the quantity of mineral in each zone, the height of each zone and the oxygen utilization within each zone.

There is also provided for the heap temperature to be maximized by minimizing the aeration rate to the heap, and for the aeration rate of the heap to be minimized by maximizing oxygen utilization of the oxygen in the heap.

There is further provided for the oxygen content to be determined by measuring the oxygen content at a predetermined point within the heap, alternatively by measuring the oxygen content of the gas emanating from the heap.

There is still further provided for the heap temperature to be determined in a predeterminable optimum area within the heap, and for the optimum area to be located within about 0.1 to about 4 meter below the surface of the heap, specifically between about 1 and 3 meter below the surface of the heap, and more specifically about up to 1 meter below the surface of the heap.

A further feature of the invention provides for a method of increasing the temperature of an ore heap to a point where the heap reaches its take-off point by aerating the heap and refraining from irrigation of the heap until the heap reaches its take-off point, and for the aeration to include blowing air at ambient temperature through the heap.

There is further provided for the method of increasing the temperature of the ore heap to include increasing heap aeration and introducing heap irrigation once the take-off point has been reached and until a predeterminable normal operating level is reached, and for the bio-assisted heap leaching process to be controlled thereafter by maintaining the optimum heap temperature through varying the aeration and the irrigation rates of the heap as a function of at least one of a determination of the oxygen content of the gas phase within the heap and a determination of the temperature of the heap.

The invention also provides for a further method of increasing the temperature of an ore heap to a point where the heap reaches its take-off point by forming a layer of granular material on a support surface, the support surface having been equipped with aeration and drainage equipment; and installing an irrigation system proximate the operatively upper surface of the layer of granular material; forming a layer of ore, inoculated with suitable microorganisms and acid stabilized, on the granular material layer; thereafter passing a hot solution through the granular layer by means of the irrigation system; thereby heating the granular layer, blowing ambient air through the aeration equipment of the support surface to react with the layer of ore until the temperature of the ore heap reaches the take-off point, thereafter terminating the irrigation flow through the granular layer, introducing irrigation of the ore layer and adjusting the aeration through the aeration equipment until a predeterminable normal optimum heap temperature is reached, and for the bio-assisted heap leaching process to be controlled thereafter by maintaining the optimum heap temperature through varying the aeration and the irrigation rates of the heap as a function of at least one of a determination of the oxygen content of the gas phase within the heap and a determination of the temperature of the heap.

There is further provided for the granular layer to comprise a layer of crushed rock.

There is still further provided for the hot solution to comprise at least one of hot PLS. (pregnant leach solution), hot solvent extraction raffinate, water or other fluid.

There is still further provided for the hot solution addition to be continued after the take-off temperature has been reached.

The invention also provides for a further method of increasing the temperature of an ore heap to a point where bio-assisted heap leaching of the heap reaches the take-off temperature by sucking or blowing hot warm air from a leached heap, which has been operated at an level substantially above ambient temperature, removing heat from said leached heap and blowing it into the first said ore heap.

It is also possible to use any one of the methods of increasing the temperature of the ore heap at any time during the leaching process to increase the temperature of the heap to the take-off point again, by maintaining an optimum heap temperature through varying the aeration and the irrigation rates of the heap as a function of at least one of a determination of the oxygen content of the gas phase within the heap and a determination of the temperature of the heap.

There is also provided for the method to include covering the heap with a layer of impermeable material, for the layer to include integral covered channels through which a solution can be passed to be heated by solar energy, thereby forming the hot solution.

A still further feature of the invention provides a method of preparing microorganisms for inoculation of an ore heap that is to undergo bio-assisted leaching, by preparing the microorganisms in a state in which the microorganisms do not produce exopolymers on their external cell walls.

There is further provided for the microorganisms to be prepared as spores or ultra micro bacteria.

There is further provided for ultra micro bacteria to be prepared by lowering nutrients in a growth medium of the microorganisms to the point where the microorganisms cease production of exopolymers on their external cell walls.

There is further provided for the lowered nutrients to include carbon, and specifically carbon dioxide dissolved in the growth medium; and for the carbon to be reduced by lowering the level of carbon dioxide in the growth medium, alternatively removing carbon dioxide from the growth medium, further alternatively using oxygen or nitrogen in the gas supply of the growth medium.

There is further provided for a method of inoculating an ore heap for bio-assisted heap leaching with the prepared microorganisms by irrigation of the heap with a solution rich in the prepared microorganisms; thereafter to activate the prepared microorganisms by irrigation of the heap with a nutrient rich solution causing the prepared microorganisms to develop exopolymers and to adhere to the external surfaces of ore particles in the heap.

There is further provided for nutrients to be supplied to the microorganisms inoculated in the heap by means of the irrigation solution of the heap, adding slow release nutrient solids to the ore or alternatively by means of aerating the heap with a nutrient aerosol and/or ammonia gas, as well as adding a carbon source via carbonate mixed with the ore or carbon dioxide added to the aeration supply.

There is further provided a method of removing iron, as well as toxic elements and organics either substantially to promote high microbial activity, with high ferrous-to-ferric conversion; or in part to reduce ferrous-to-ferric conversion to achieve a lower redox potential within the heap.

A further feature of the invention provides a method of determining an optimum heap configuration for a bio-assisted heap leach process of an ore heap; by measuring the leaching rate, the heat of reaction, and the sulphide content of the ore; and determining maximum aeration and irrigation rates and an optimum heap height.

A still further feature of the invention provides for a sulphide concentrate fuel to be added to an ore heap during stacking thereof, for the sulphide concentrate fuel addition to be used with ores that take a commercially unacceptable period to achieve the take-off temperature if treated with prior art processes; and for the sulphide concentrate fuel to be pyrite or other suitable sulphide concentrate.

There is also provided for an ore heap with added sulphide concentrate fuel to be brought to take-off temperature by means of any of the methods of increasing the temperature of a heap, and thereafter to be operated according to the method of controlling a bio-assisted heap leaching process by maintaining an optimum heap temperature through varying at least one of the aeration and irrigation rates, as described before.

#### **BRIEF DESCRIPTION OF THE DRAWINGS**

Embodiments of the invention will be described below by way of example only and with reference to the accompanying drawings in which:

Figure 1 shows the effect of varying the aeration to irrigation ratio ( $G_a/G_i$ ), with two different methodologies;

Figure 2 presents a family of curves of average heap temperatures versus  $G_a/G_i$  ratio at different power generation rates, and hence different oxidation rates;



Figure 3: illustrates heat being washed out of a hot heap over time by over irrigation;

Figure 4a demonstrates the effect of moving out of the optimum  $G_a/G_l$  range, as would occur under an upset condition for a particular setup;

Figure 4b shows the point at which the rate of change of temperature is highest in the example of Figure 4a;

Figure 5a demonstrates the effect of moving out of the optimum  $G_a/G_l$  range, as would occur under an upset condition for a different setup to that of Figure 4a;

Figure 5b shows the point at which the rate of change of temperature is highest in the example of Figure 5a;

Figure 5c shows the point at which the rate of change of temperature is highest in the example of Figure 3;

Figure 6 shows the effect of oxygen utilization on average heap temperature at various  $G_a/G_l$  ratios;

Figure 7 shows the effect of a decrease in the oxidation rate (and power generation in  $W/m^3$ ) over the leach cycle; which requires a new optimum  $G_a/G_l$  ratio along with an optimum absolute aeration rate, requiring a change in the irrigation rate for that particular system over the leach cycle;

Figure 8 shows that the optimum  $G_a/G_l$  ratio and average heap temperature is different for different heap heights;

Figure 9 shows an example of a 12-metre heap operated at over three phases of oxidation rates corresponding to a power generation of 80, 40 and 10 W/m<sup>3</sup>;

Figure 10 shows an example of an 18-metre heap operated over three phases of oxidation rates corresponding to a power generation of 10, 5 and 2 W/m<sup>3</sup>;

Figure 11 shows the sensitivity of average heap temperature to the  $G_a/G_l$  ratio for higher oxidation and therefore power generation rates;

Figure 12 shows the temperature take-off effect in bio-assisted heap leaching;

Figure 13 shows an example in which water, at a temperature of 40°C is passed through a granular layer at a rate of 2.5l/m<sup>2</sup>/hour and air blown at rate of 0.72kg/m<sup>2</sup>/hour;

Figure 14 illustrates an example of first ore to be leached in which a granular layer is placed on a pad, which has been equipped with a drainage system as well as an aeration system;

Figure 15 illustrates another example of first ore to be leached in which a granular layer is placed on a pad, which has been equipped with a drainage system as well as an aeration system;

Figure 16 illustrates the addition of further ore on the example of a heap illustrated in Figure 15.

### DETAILED DESCRIPTION OF THE INVENTION

The fundamental Dixon approach to finding the optimal operating conditions is flawed. The solution, in a typical heap leach operated at present, is the fluid in which the metal dissolves and is subsequently recovered by solvent extraction; it is also the medium to add acid during the leach cycle and the main reaction medium. The air, as Dixon correctly indicates, has an important effect on temperature. However the main and overwhelmingly important function of the air is the supply of oxygen for the oxidation reactions. The applicants have determined that the air supplied to the heap must at least satisfy the stoichiometric requirements for the oxidation reactions, a factor that Dixon seemingly did not consider in his publication. So far as the applicants are aware, oxygen utilization in heaps has not been actively studied, but in mesophile tank bioleaching systems, 38-44% is considered best practice, as indicated in WO 00118269A1. For the purposes of illustration in the first instance an oxygen utilization of 25% was assumed, to derive a minimum airflow to satisfy a specific and fixed oxidation requirement for a particular heap height. Although air does push heat up into the heap, it also has a cooling effect at the bottom of the heap. Ideally, therefore, the air should be the minimum required to satisfy oxidation requirements and irrigation should be varied so as to just maintain a net positive advection coefficient.

The heap described earlier, 6 meters in height, at a fixed oxidation rate giving a power generation of  $20\text{W/m}^3$ , only requires about  $0.15\text{ kg/m}^2/\text{hour}$  of air to satisfy the stoichiometric requirements, which were assumed to be  $2.0\text{kg}$  oxygen per  $\text{kg}$  of sulphide, given 100% oxygen utilization. However, given 25% utilization the air requirement amounts to  $0.59\text{kg/m}^2/\text{hour}$ . The latter therefore represents the airflow giving the minimum cooling effect at the bottom of the heap, given the maximum oxygen utilization assumed. The applicants have established that by varying the irrigation rate, a net positive advection coefficient can be achieved, which maximizes heap temperature at a given aeration rate. The effect of these

steps is to increase the average heap temperature of about 38°C found by Dixon, at a power density of 20W/m<sup>3</sup>, to about 52°C, which is significant since this is approaching the minimum temperature at which chalcopyrite would be expected to fully leach; in both cases applying the identical computational methodology to Dixon. The data is presented for comparison in Figure 1.

The major shortcoming of Dixon's computational methodology is that sulphide oxidation rates are assumed uniform throughout the heap, irrespective of temperature. In fact the oxidation rate will be a strong function of temperature. Since the temperature profile within the heap is quite variable, then the oxidation rates will also be variable. In effect the heat generation in the cooler parts of the heap (i.e. at the top and bottom) will be lower, further reducing the temperature in these areas. Thus the temperature estimates given in Dixon's work, are likely to be too high at the top and bottom of the heap (biasing the average heap temperature too high). The applicants have improved on the method of Dixon by varying the rate of reaction according to temperature, using the Arrhenius equation, assuming an activation energy of 20500kJ/mol. The methodology used in determining the data presented Figure 2 (described hereinafter) was per Dixon's computational methodology, excepting that the reaction rate was varied according to the Arrhenius equation. Required aeration rates, in this example and those following it, were calculated using a stated and assumed oxygen utilization, a fixed power generation per cubic meter, a reaction heat of 25000kJ/kg sulphide, an oxygen requirement of 2.0kg/kg sulphide; all to suit the heap height used. All the other assumptions were per Dixon, excepting surface heat transfer coefficient, which was taken at 5W/m<sup>2</sup>/°C (Dixon's 20 W/m<sup>2</sup>/°C is too high in the applicants experience). A family of curves, representing different power generation rates (and hence oxidation rates) is presented in Figure 2; the air requirements at 25% oxygen utilization are also shown on the curves. It can be seen that at higher oxidation rates (corresponding to 80, 40 and 20W/m<sup>3</sup>) the  $G_a/G_i$  peak is quite pronounced, with the average temperature dropping off severely once the  $G_a/G_i$  ratio falls even slightly below optimum. The drop off is

less severe at  $10\text{W/m}^3$ , but again average heap temperature reduces. At a low oxidation rate (corresponding to  $5\text{W/m}^3$ ) the average heap temperature drops even further; also there is no clear maximum  $G_a/G_i$  ratio. In solving these equations it is apparent that at below the critical  $G_a/G_i$ , the system does not quite reach steady state, then moves away from steady state rapidly as the system becomes "negatively autocatalytic". That is to say as the amount of heat generated is reduced below the cold front, the enthalpy in the air moving upwards becomes grossly insufficient, in the face of cooler solution coming down, to prop up the temperature which collapses, as demonstrated in Figure 3.

Figure 4a demonstrates the effect of moving out of the optimum  $G_a/G_i$  range, as would occur under an upset condition. In this example a heap at steady state with a power generation of  $20\text{W/m}^3$  (operating at the optimum  $G_a/G_i$  ratio of about 0.35) is given a step change down to  $5\text{W/m}^3$ , the irrigation and aeration rates remaining constant. Such a change in power generation could come about, for example, by a reduction in microbial activity due some extraneous factor.

It can be seen from Figure 4a that the heat is washed out from the heap as time progresses, because the aeration and irrigation rates are both too high. Two things are required to maintain the heap average temperature in this case. Firstly the aeration rate must be reduced to match the requirements of the oxidation reactions (at a given oxygen utilization). Secondly the irrigation rate must be reduced to bring the  $G_a/G_i$  ratio back to the new, and in this instance, higher optimum point.

The applicants have also established that the point at which the rate of change of temperature is highest, in this example, is just under one meter below the heap surface, as can be seen from Figure 4b, which shows change in temperature with respect to time at different depths within the heap. It can be seen from Figure 4b that after just ten days following the drop in power generation, the temperature just under a meter below surface has dropped by about  $11^\circ\text{C}$ . After twenty days

the temperature has dropped by about 21°C. The rate of temperature drop at the peak point is about 1°C per day over the first twenty days. The actual point at which the temperature changes will be different for different systems, but fairly near to surface. For example Figures 5a and 5b show a different system, with a 12-meter heap and 50% oxygen utilization. In this example the most sensitive point is about 0.5 meter from surface. The rate of temperature drop at the peak point is about 2.5°C per day over the first ten days. Under a more severe upset condition (such as the example given previously in Figure 3) the region below surface where the temperature drops, as shown in Figure 5c, is about 0.3 to 0.5 meter below the heap surface. The rate of change in temperature in the region of the peak point is about 18°C in the first day, 10°C in the second day and declining to about 7°C per day over the next two days.

It was mentioned previously that a lower gas flow would result in less cooling at the bottom of the heap, increasing average heap temperature. If the oxygen utilization is 50% then the required aeration rate is halved over what was previously assumed and the cooling effect is reduced at the base of the heap - increasing the average heap temperature, as seen in Figure 6. Increasing oxygen utilization to 75% further increases average heap temperature. Also the optimum  $G_a/G_i$  ratio is lowered in both the 50% and 75% oxygen utilization cases (in comparison with the 25% case), demonstrating that the optimum  $G_a/G_i$  ratio is also function of the absolute aeration rate, for a given system. The applicants have therefore established that oxygen utilization will play a significant role in achieving high heap temperatures, by minimizing the absolute air addition to the heap.

Another of the shortcomings in Dixon's work was the assumption that the sulphide oxidation rates are constant throughout the life of the heap and that the sulphide minerals all oxidize at the same rate. In reality the oxidation rates are likely to be higher at the beginning (assuming the ore is at an elevated temperature to start with), with readily oxidized mineral phases leaching first and

less readily oxidisable mineral phases leaching later on. Thus the oxidation rate will peak early on in the life of the heap and decline thereafter.

Early on in the life of an active heap relatively high rates of irrigation will be required to remove leached metal and to help cool the heap; i.e. the power generated will be relatively high in  $W/m^3$ . Aeration rates will have to be similarly high to provide sufficient oxygen for the oxidation reactions, as well as optimally distributing the heat within the heap. There will be an optimum,  $G_a/G_l$  ratio and aeration rate for that particular system at that point in the leach cycle. As the life of the heap progresses, fewer readily oxidisable sulphides will be available and the oxidation rate (and power generation in  $W/m^3$ ) will decline. With such a decline the optimum  $G_a/G_l$  ratio will change, along with absolute aeration rate, requiring a change in the irrigation rate. Towards the end of the heap leach cycle, the readily oxidisable sulphides remaining will be lower still and so will be the oxidation rate (and power generation in  $W/m^3$ ). Once again there will be a new optimum,  $G_a/G_l$  ratio along with an optimum absolute aeration rate, requiring a change in the irrigation rate for that particular system. Figure 7 illustrates this concept schematically.

Consequently the absolute rates of irrigation and aeration must be adjusted, during the whole leach cycle, using temperature measurements, especially in a region up to about one meter below surface, as well as oxygen level measurements in the gas phase in order to determine how closely the air meets the oxidative requirements, as well as to maximize oxygen utilization. Oxygen levels could be measured in the off gas, or with more difficulty at different levels in the heap. The temperature measurement will be complicated to some extent by changing climatic conditions, as well as the day/night cycle, so a point somewhat lower down in the heap, where these effects are reduced may be more practical in some instances.

Additionally it is apparent to the applicants that heat losses via the heap surface or PLS are a strong function of surface area; thus given an irrigation and aeration rate (which are expressed in litre or kg per m<sup>2</sup> per hour) in a certain climate and at a given W/m<sup>3</sup>, increasing the heap height will increase the energy released, whilst maintaining the same heat losses or gains; overall a higher average heap temperature should result. However in these circumstances oxygen demand will also have increased, requiring, at the same oxygen utilization, an increase in aeration proportional to the heap height increase; such an increase will give additional cooling at the base of the heap. However heap height will nevertheless be a useful variable in the design of a particular system, as illustrated in Figure 8, and forms another aspect of the invention. It can be seen from Figure 8 that the optimum  $G_a/G_i$  ratio is different for different heap heights. Additionally, in this example, it can be seen that there is a slight reduction in average heap temperature in going from a heap height of 12 to 18 meter. Likewise, the short heap height (4 meter) is also a poor performer, the average heap temperature being about 13°C lower than the 6 meter heap.

In hilly or mountainous terrain, relatively flat surfaces are often unavailable, or can only be prepared at significant cost. In such cases ore may be stacked in valleys or other areas where the height of ore, will be dictated by geography. In such instances different irrigation and aeration rates can be applied in different zones, corresponding to different heap heights, over the duration of the leach cycle, which is another aspect of the invention.

It will be appreciated by those skilled in the art that the heterogeneous nature of the ore in heaps will require a plurality of measurements of both temperature and oxygen content at least in two dimensions and more likely three dimensions. Such heterogeneity may dictate the need for additional flexibility in changing both aeration and irrigation rates over relatively small zones of the heap surface. Additionally operating at a  $G_a/G_i$  ratio slightly higher than the theoretical optimum will be a more robust operating strategy in some instances.



By way of a very simple example Figure 9 shows a 12-meter high heap operated over three phases. The first phase is at an oxidation rate corresponding to  $80\text{W/m}^3$ , the second to  $40\text{W/m}^3$  and the third to  $10\text{W/m}^3$ . The average heap temperature ranges from  $61$  to  $63^\circ\text{C}$ , which is about the lowest temperature that could be expected to fully leach chalcopyrite.

The invention can also be used on ores with very low sulphide contents. An exercise similar to the previous one was determined, but with three phases corresponding to  $10$ ,  $5$  and  $2\text{W/m}^3$ , which indicated an average temperature of about  $61^\circ\text{C}$  could be achieved, as shown in Figure 10. As seen previously, at low oxidation rates the system is a lot less sensitive to the  $G_a/G_i$  ratio, but nevertheless the absolute values of both need to be controlled to maximise heap temperature, because high irrigation rates can nevertheless wash heat out from the heap. The energy release in the  $10\text{W/m}^3$  phase corresponds to the total oxidation of about  $1.6\%$  sulphide in eight hundred days, reasonably low and a level that many economic ores will contain. The eight hundred days is the time it takes for the heap to get to steady state (in comparison an  $80\text{W/m}^3$ , six meter high heap will achieve steady state in less than 50 days). However if the heap started off at a higher temperature, for example by applying external energy (as will be described later), then the total cycle time could reduce to two hundred days, in such case the total sulphide oxidised amounts to just less than  $0.3\%$ , an unexpected and remarkably low content. It will be noted from Figure 9 that at very low power generations the point at which temperature will drop in an upset condition will lie about 3 to 4 meter below surface.

The finding that high sulphide contents are not a pre-requisite to achieving high temperatures within heaps is significant, as many have believed that the addition of fuel, in the form of sulphide concentrates to be necessary and this is clearly not the case. Although sulphide concentrates will be readily available to the oxidation process and thus will increase rates of temperature rise, they will not

increase ultimate heap temperature that much; rather minimizing aeration, by maximizing oxygen utilization and operating at an optimum  $G_a/G_i$  ratio is the key.

However, in the case of ores with a low rate of oxidation and low sulphide content, leading to a commercially unacceptable time period to reach the take-off point, the addition of a sulphide concentrate fuel to the heap would assist in bringing up the heap temperature at a faster rate.

The invention can also be used on highly reactive ores with high sulphide content. If an ore containing a much higher sulphide content of, for example, around 7% is considered, then power generations of  $200\text{W/m}^3$  are quite readily achievable. The sensitivity of average heap temperature to the  $G_a/G_i$  ratio is shown for a high power generation in Figure 11, with  $80\text{W/m}^3$  shown for comparison. Because the aeration rate to supply sufficient oxygen at 25% utilization is that much higher, there is more cooling at the base of the heap, thus average heap temperature is not, in fact, much different from the  $80\text{W/m}^3$  power generation case. Once again though the system is sensitive to the  $G_a/G_i$  ratio and if the power generation drops, then heat can be washed quickly from the heap. The point at which the temperature declines under upset conditions in this case is barely below surface, for example 0.1 meter below surface.

In the case of a pre-treatment process for refractory gold the invention could be used for controlling heap temperature at a high, and optimum level, by irrigating with cold water rather than raffinate.

In summary at this point the applicants have established that the absolute aeration and irrigation rates, as well as the ratio between them, are very important factors in determining the average heap temperature, and that these variables require significant adjustment for different oxidation rates and heap heights in a given location. Additionally the applicants have established there exists a region in the heap, between near surface and typically up to a meter

below the surface, at which temperature changes rapidly (relative to heap leach cycle times), in an upset condition (up to 4 meters below surface at very low oxidation rates). Also that to maximize heap temperature the air addition to the heap must be minimized, by maximizing oxygen utilization. Since reaction rates are invariably not linear the oxidation rate will decline in some manner with respect to time, and the *in situ* power generation will drop with time. The only way to maintain the average heap temperature at a high and optimum level is to vary at least one of the irrigation and aeration rate according to the temperature in the heap, especially about up to a meter or so below surface, as well as according to the oxygen content of the gas phase within or emanating from the heap. In an upset condition the oxygen level of the gas will change rapidly, within hours, giving an early indication that all is not well in terms of sulphide oxidation. A subsequent temperature drop about one to ten days later, in a region typically up to about a meter or so below the heap surface will confirm this. In conditions where the sulphide oxidation rate declines as a result of the oxidation rate declining gradually (due to reaction kinetics for example), oxygen levels in the gas phase will rise, requiring a reduction in irrigation rate to maintain the optimum Ga/GI ratio, and therefore the optimum heap temperature, over the leach cycle. One of the major advantages of this aspect of the invention is that since heap temperature is maximised by providing sufficient aeration, at the maximum possible oxygen utilization, as well optimum irrigation, throughout the leach cycle, there is no need to know the individual oxidation rates of the different sulphide species.

Additionally it will be appreciated by those skilled in the art that indirect methods also exist for determining changes in oxidation rate, for example, a single or multiple determination of wet and dry bulb temperatures of the gas phase, solution redox, solution oxygen, solution metal content (especially recovered metal content), solution temperature (especially exiting the heap), oxygen and carbon dioxide uptake rates within the heap, as well as predictive modelling based at least on feed composition, heap geometry, location and climate. Also it

will be appreciated that whilst control algorithms may be necessary to manipulate the air and irrigation rates in certain circumstances, in other circumstances manual control may suffice.

Previously it was said that oxidation rates will be highest at the beginning of the cycle and this is true, providing the heap is already at an elevated temperature when the oxidation process starts.

The most difficult aspect of heap leaching of copper ores, particularly those containing chalcopyrite, is being able to start the leaching process at a high oxidation rate. Typically sulphide ores will be at a low temperature when they have been mined, typical Chilean ores, for example, will have been mined at an ambient temperature of around 10°C. At these temperatures, the only sulphide mineral that leaches readily will be chalcocite, the generally more abundant pyrite will only leach to a very limited extent and chalcopyrite hardly at all. Even then, the chalcocite leaches fully only very slowly in commercial operations, with typical leach cycles well in excess of one year. The only way to speed up the oxidation process is to increase the temperature, but this represents the classic "chicken and egg". The sulphides won't readily oxidise unless the temperature is increased, but the temperature won't increase until the sulphides begin to oxidise. Clearly what is required is to "kick-off" the process, which brings us to another aspect of the invention.

To those skilled in the art, the ability of microbial systems to "take-off" (i.e. to become autothermal) is well known in tank bioleaching systems, where at some point after starting the bioleach reactors, external heat no longer need be applied and the system becomes autothermal. Soon thereafter the bioleach tanks require cooling. The applicants are aware that the same effect has been documented in sulphide heap leaching, although generally under uncontrolled conditions. This is illustrated schematically in Figure 12. What is required to achieve the high temperatures, especially to leach chalcopyrite, or reduce leach

cycle periods in other systems and to increase ultimate metal extraction, is to consistently increase the heap temperature to a point where the system takes-off. The take-off temperature point will be different for different systems, as well as taking a different time period in different systems. For example, where a heap contains readily oxidisable sulphide species (for example pyrrhotite) the heap may well take-off at a relatively low temperature and do this quite quickly in, for example, a few weeks; indeed cooling, rather than kick-off, may be the greatest issue in managing the overall leach cycle.

Bringing the heap to the take-off temperature can be achieved by one of two methods in the invention.

Firstly let us consider a favourable scenario, where the ambient climate is favourable and/or the major sulphide species will oxidise readily (for example pyrrhotite in nickel sulphide ore). The ore can be inoculated, using suitable microorganisms, or a mixture thereof, preferably as the heap is stacked, along with any sulphuric acid required. No irrigation solution is applied during the kick-off phase. The ore heap is then blown with air at a volumetric flowrate sufficient to commence and then continue the oxidation process in the heap. The air will become warmer and more humid as it passes through the heap. As the warm humid air passes up through the heap, it warms up a portion of the ore above the bottom layer until that portion begins to oxidise and increase in temperature. So this process continues until the entire heap (excepting the surface layer, which is subject to the vagaries of day/night temperature cycles) becomes rapidly heated to the take-off point. The energy required, heating the ore heap, as well as the air and contained moisture, by 20°C is in the order of 40MJ/m<sup>3</sup>. Such energy can be obtained via a very limited amount of sulphide oxidation ~0.5kg/m<sup>3</sup>, compared to the more typical contained sulphide of ~5-100kg/m<sup>3</sup>. Because the air flowrate is relatively low, so is evaporative cooling; also there is no irrigation applied to remove heat via PLS. Such a system could reach the take-off temperature point quite quickly, for example in a few weeks.

Once the heap has reached the take-off temperature point, solution irrigation and aeration can be gradually increased to the operating level and the heap is brought up to the desired operating temperature. Thereafter the heap temperature is kept at an optimum level, as previously described.

The first case is the easiest because of high ambient temperatures and/or readily oxidisable materials and the heap is brought up to the operating temperature completely autogenously, without the introduction of external heat. However, most commercial copper ores suitable for heap leaching do not contain readily oxidisable materials, generally the main sulphide species being pyrite, which is quite difficult to oxidise. Also many of the deposits are located at altitude and have low ambient temperatures. In these cases it may be possible to irrigate the heap with warm solution (for example intermediate leach solution, from an older heap). Such irrigation serves in order to bring the heap temperature up, but as noted earlier, only by a few degrees at best, which brings us on to other aspects of the invention.

Typically heap-leaching operations are operated in two fashions. Firstly there is the fixed pad system in which the leach pad is prepared with a thin layer of crushed rock, in which is placed, a solution drainage system and an aeration system. In the fixed pad system ore is initially stacked and leached over a portion of the ultimate pad area. After leaching, new ore is placed on new areas of the pad as well as on the old heaps and the new ore is leached. Eventually the pad is fully covered with leached or leaching ore and thereafter all the new ore is leached on top of the old heaps. Once ore has been leached according to the method of the invention, the ore heap will be at a high operating temperature, in the case of chalcopyrite probably around 60°C. In this instance an old, leached, heap will roughly equal the volume of a new ore heap and have sufficient enthalpy to at least heat the new ore heap to the take-off temperature point or even higher. The new ore heap is inoculated and acid stabilised as

previously described and the aeration system at the base of the old heap is used to blow air from the leached ore into the new ore heap above it, transferring the heat into and rapidly raising the temperature of, the new heap above it, to at least the take-off point or possibly an even higher temperature. Such a method is also described in US 6110253. Thereafter the temperature is kept at an optimum level, as previously described.

According to another aspect of the invention, the blower feeding a heap on a first level heap (that is to say one of the first heaps placed on the pad), may at the completion of leaching be reversed to suck rather than blow. Alternatively any other suitable device can be used to withdraw the heat from the heap. The warm moist air sucked from the heap can then be fed into another heap that is just about to start the cycle, rapidly increasing the new heap's temperature as described in the previous paragraph. Thereafter the temperature is kept at an optimum level, as previously described. There will be other methods of drawing heat from the old heap, for example by blowing the heat out and capturing the warm gas at the top of the heap for distribution.

It will be appreciated that the ore in the cooler parts of the heap will not leach fully, but will have another opportunity to see hot solutions from later heaps placed on top, which is not the case in the on-off system considered next.

The second way of operating heap-leaching plants is the so-called on-off system. In the on-off system the ore is placed on a pad, on which a thin layer of crushed rock at the base as well as suitable drainage and aeration systems have been installed. The heap is stacked with ore and then has an irrigation system installed on the top surface. The ore heap is leached and when the cycle is completed the leached ore is removed (leaving the thin crushed rock base layer and aeration and drainage systems intact) and new ore is placed on the pad and a new irrigation system installed on top of the new ore. The removal of leached ore and the addition and leaching of new ore can continue indefinitely in a cyclic

fashion. In the case where the old heap temperature is high the heat will be lost, since the old heap is removed and discarded. In another aspect of the invention, the aeration system or other suitable device, at the end of the leach cycle, is used instead as a suction device (for example by reversing the direction of the blower fans). The warm and humid gas is then sucked from the old heap can then be diverted to a newly established heap as described in the second part of the fixed pad system earlier. Again, there will be other methods of drawing heat from the old heap, for example, by blowing the heat out and capturing the warm gas at the top of the heap for distribution.

However in both the fixed pad on on-off systems at least the first initial heap or heaps have to reach the take-off point and desired operating temperature. Additionally the heaps will at some point during the project life become out of synchronisation. In the favourable scenario the climatic conditions and/or the presence of readily oxidisable materials will favour bringing the heap up to the take-off temperature completely autogenously i.e. without the addition of any external heat. In cases where the opposite applies i.e. cold climatic conditions and less readily oxidisable sulphides, it may be necessary to add some external heat, particularly if the take-off temperature is to be reached in a commercially acceptable time period. As mentioned previously the heating of irrigation solution is an inefficient means of increasing heap temperature, especially in colder climates. Mintek's proposal in WO 00/71763 A1 to add hot, humidified, air to the heap would be more efficient. However the addition of such air does not have to be for the duration of the leach cycle, only for the period necessary to bring the heap to the take-off temperature.

An additional method of bringing the heap up to the take-off temperature, which is another aspect of the invention, is to form a layer of granular material, of a pre-determined thickness, on a pad, the pad having been equipped with a suitable aeration and drainage system. Near the top of the granular material layer is installed a permanent and robust buried irrigation system. Fresh ore is then



stacked on the layer of granular material, suitably inoculated and acid stabilised. Hot solution (including hot PLS or heated solvent extraction raffinate or water) is passed through the layer of granular material using the buried irrigation system installed at the top of the layer of granular material. If hot PLS is used it has the advantage of being able to be continuously added, without concerns regarding dilution of the solution inventory. At the same time ambient air is blown into the base of the layer of granular material within the heap. The layer of granular material forms a surface, on which heat is transferred from the warm solution to the incoming air, which then passes through the ore heap, increasing its temperature to the take-off point. By way of example, the concept is illustrated in Figure 13, in which water, at a temperature of 40°C is passed through the layer of granular material at a rate of 2.5l/m<sup>2</sup>/hour and ambient air blown into the granular layer at rate of 0.72kg/m<sup>2</sup>/hour. The gas exiting the layer of granular material is at about 40°C and nearly fully saturated and is well suited to rapidly heating the ore heap above it. The hot water or solution can be from any source, for example, PLS from elsewhere in the system, solvent extraction raffinate, waste heat from power generation or cooling fluid from bioleaching stirred tank reactors (both directly or indirectly) or other stream above ambient temperature, including fluid warmed using solar heating, or other heat bearing fluid with heat suitably transferred from any source outline previously via a heat exchanger. Once the take off temperature has been reached in the ore the hot water or solution addition at the top of the layer of granular material is stopped. Then solution irrigation and aeration can be gradually increased to the operating level in a controlled manner, and the heap brought up to the desired operating temperature. Thereafter the heap temperature is kept at a near optimum level, as previously described.

Another advantage of this method is that once the leaching of the ore takes place, the layer of granular material continues heating the rising air and cooling the PLS, thereby reducing heat losses to the PLS and increasing the average heap temperature by at least about 1°C. This is especially useful where

oxidation rates are relatively low and the PLS is relatively hot (the low aeration rate giving less cooling at the base). In effect the cold "tail" of the heap is brought outside the ore into the layer of granular material, where temperature is unimportant because there is no leaching. Thus even in favourable circumstances where the heap can be brought up to temperature autogenously, there would be an advantage in using such a layer of granular material at the base of the heap, because it will move the cold "tail" of the heap outside of the ore and increase average heap temperature. The layer of granular material could be crushed rock, sand, gravel, synthetic material or even a heat exchanger external to the heap. The thickness of the layer of granular material is dictated by practicality more than any other criteria, but must have good surface area and remain permeable over the course of time. In the fixed pad system the previously leached ore may act in place of the layer of granular material. Even if the hot solution were added indefinitely for all freshly stacked ore heaps the cost would be modest (assuming purchased energy) at less than US\$2/lb copper for a typical copper heap leach. In practice though the system would not operate continuously on all new heaps and thus the cost would reduce.

In the event a higher temperature than about 62°C is required, PLS solution can be bled from the system, heated (for example by using hot water or other solution in a heat exchanger, or using solar heating) and then recycled back to the layer of granular material. In this way ambient air entering the heap is warmed and humidified throughout the leach cycle, and forms another aspect of the invention. Alternatively the ambient air can be warmed and humidified before entering the heap, for example by steam injection.

Although both the two previous steps require the application of external energy, which will add to cost (unless waste or natural heat is used, for example from stirred bioleach tank vessels, or from solar heating), such cost may be warranted by additional copper that is recovered. It will be appreciated that in heating and humidifying the air going into the heap will change again the optimum  $G_a/G_l$  ratio

for a given system, since the irrigation solution has to overcome a greater upward heat flux from the warm and humid air. For heap that has a rapidly dropping temperature under an upset condition, the addition of hot humid air would be a useful control tool.

According to another method of the invention, with ores that take a commercially unacceptable period to achieve the take-off temperature, for example eight hundred days, a sulphide concentrate fuel, for example pyrite, may be added to the ore heap whilst it is being stacked. The heap is then brought up to the take-off temperature by any of the methods previously described, and then operated according to the methods as also previously described.

It will be appreciated that heap temperatures can be improved by other methods. For example irrigation solution can be applied intermittently, for example during daylight hours only; as well as periodically to achieve the low rates needed during very low oxidation phases, or both.

Ambient conditions (wet and dry bulb temperature etc.) can be measured continuously in order to provide data to the control system.

Notwithstanding the fact that applying hot irrigation solution has a relatively small effect on average temperature, even that small effect would be beneficial. Consequently design of solution drainage, irrigation and general handling systems should be carried out to minimize heat losses where practical. Irrigation slightly below the surface will help reduce immediate evaporation losses and reduce the overall surface heat transfer coefficient.

The use of plastic covering for the heaps with integrated solar heating channels to warm either irrigation or other solution or preferably recycled PLS will assist in maintaining a high temperature within the heap.

It will be appreciated that the invention can be used during the kick-off and start-up of the heap, with aeration being adjusted to supply the oxidation reaction requirements, according to the oxygen content of the gas phase within or arising from the surface of the heap to maximise the rate of increase in heap temperature. Substantially no irrigation will be applied during the kick-off period, but will gradually be applied in the start-up phase according to temperature measurements within the heap. For reactive heaps high temperatures will appear close to the surface quite quickly, in days or weeks, in less reactive heaps the process will be slower and best monitored using a plurality of temperature measurements at different depths within the heap.

The rate of dissolution of sulphide minerals is dependent on the catalytic action of microorganisms in the heap. In both the start-up phase and the operational phase of the heap operation, these microorganisms play a critical role. It will be noted by those skilled in the art that the likely operating temperature of heaps, operated according to the method of invention, will barely fall in the range of operation of extreme thermophiles. Thus a mixture of suitable mesophiles and moderate thermophiles will find more application for most high temperature heap leaching applications; suitable extreme thermophiles only being required in some instances, especially those involving leaching of chalcopyrite. It will be necessary to inoculate the heap with suitable bacteria and/or archaea that catalyse the oxidation of sulphide minerals. The suite of microorganisms used will depend on the ultimate desired heap operating temperature and the temperature ranges the heap passes through as it moves towards its final operating temperature. It is preferable the heap is inoculated, with as concentrated an inoculum as possible, during the stacking process, so that all the microorganisms required will be *in situ* when oxidation commences and are immediately available for ferrous-to-ferric conversion. However in the case where particle size is large (run-of-mine heap or dump leaching for example), an intimate mix of microorganisms and the ore will be difficult to obtain. Residue

from a stirred tank bioleach plant or plants would also be suitable as an inoculum.

By inoculating these heaps simply by irrigating the heaps with a solution enriched with suitable microorganisms, the microorganisms will not penetrate the depth of the heap. Rather, they will stick to the rocks and minerals at the point of irrigation or injection, thus forming a "skin" of microorganisms at the surface of the heap. This is because the external cell walls of the microorganisms are coated with exopolymers that are adhesive. In fact, this property of the adhesive nature of microorganisms is the basis for the effectiveness of sand filters in the purification of water.

Thus it is very difficult, to inoculate the entire body of the heap with microorganisms in their normal vegetative state by simply irrigating the heap with inoculum; at finer particle sizes it will become virtually impossible.

However, bacteria and archaea that have been specially treated to reduce the production of polymeric material on the external surface of their cell walls will penetrate the heap and will not stick to the mineral and rock surfaces of the heap. Such a preparation of microorganisms will enable the heap to be fully inoculated, and will allow the catalytic effect of the microorganisms to resume leaching, allowing the more optimal operation of the heap.

Bacteria and archaea can be prepared as either spores or ultra micro bacteria (UMB). In this state, the microorganisms do not produce polymers on their external cell walls. The heap can be inoculated with microorganisms in this state by irrigating the heap with a solution enriched in the spores or ultra micro bacteria, and once the spores or UMB enriched solution has fully penetrated the heap body of the heap, the spores or UMB can be resuscitated from their vegetative state.

Ultra micro bacteria are produced by certain bacterial strains by successive lowering of the nutrients in the growth medium. "Starving" the cells in this way will cause them to cease the production of the exopolymers on the external surface of the cell wall that result in their adhesive nature, and, in some cases, cause them to reduce in size. The reduced-size cells are called ultra micro bacteria. The important property of this starvation treatment for this invention is not the production of ultra micro bacteria or spores, but that bacteria treated in this way do not stick to porous media, and can easily penetrate and effectively inoculate a heap.

The production of microorganisms with reduced exopolymers by starvation is most often achieved by reducing the carbon source in the growth media. In the case of microorganisms suitable for heap leaching, the carbon source is often carbon dioxide dissolved in solution. Preparation of the starved cells is achieved by removing carbon dioxide from the solution or limiting the concentration of dissolved carbon dioxide, such as by removing carbon dioxide from the air source required for the growth of the microorganisms, or by using pure oxygen and nitrogen in the gas supply to the growth culture. The reduction of the exopolymers may also be achieved by limiting a nutrient other than the source of carbon.

Thus, this part of invention concerns the method of preparing microorganisms prepared in reactor by a suitable starvation method, injecting them into the heap or dump, and then resuscitating them, either by injecting a nutrient rich solution into the heap or dump, or by allowing the microorganisms to naturally revert back to their vegetative state. Using this aspect of the invention it will be possible to re-inoculate a heap or dump during it's operating life. For example a simultaneous failure of air and irrigation supply to an active heap will lead to high temperatures, high enough to kill all the microorganisms; this aspect of the invention could be used to re-inoculate the heap after the air and irrigation supply has been restored and resume leaching thereafter. Additionally this aspect of the

invention could be used to re-inoculate old heaps or dumps, leach the heap or dump by methods described previously and extract further values from them.

Because the ability to control aeration and irrigation rates freely during the leach cycle is an important aspect of the invention it is necessary to ensure that the heap does not become impermeable to air or solution during the leaching process, by for example clogging up with clayish materials. Newmont in US 5834294 indicate a method of avoiding the blinding of heaps by the addition of acid resistant polymers to the ore during the agglomeration process prior to leaching. The applicants are of the opinion that such a process may be useful in some cases of application of the invention to avoid such blinding.

A limited bleed of solution (via moisture retained in leached material) takes place in typical heap leaching operations. It is therefore possible that deleterious elements may build up in solution, for example aluminium, as well as organic material from the solvent extraction process. Both organic material and aluminium are known to be toxic to microorganisms. In order to maintain a healthy microbial system, it may be necessary to remove aluminium from solution on a bleed stream of the PLS or raffinate solutions, for example by precipitation at an elevated pH with limestone. Organics could be removed by adsorption onto carbon, or biologically using suitable microorganisms. Additionally any surplus iron or sulphuric acid could also be removed on this stream, by precipitation with limestone for example; pyrite oxidation being certain to increase levels of both. Iron and acid could also be removed by irrigating old heaps, or copper-oxide heaps/dumps or other basic (alkaline) rock heaps. However, if a low redox system proves to be advantageous, as indicated by Mintek, and mentioned earlier, then some restriction on microbial growth may prove beneficial, reducing the conversion of ferrous to ferric and keeping the redox relatively low. Such a restriction could be maintained by limiting the bleed from the system. Alternatively severely restricting the airflow may achieve the same

effect. Organic toxicity could be avoided altogether by using ion exchange instead of solvent extraction.

The methods described by Geobiotics, for example in US 6107065, in which fines, usually concentrates, are variously coated onto a coarse substrate and heap leached are also well suited to the invention.

The invention is capable of treating any metal sulphide by oxidation and leaching in heaps, not just copper and nickel. In the case of a pre-treatment process for refractory gold the invention could be used for controlling heap temperature at a high, and optimum level, by irrigating with cold water rather than raffinate.

The invention can also be used as a means of maintaining heap temperature in the event of rainfall events, normal irrigation ceasing (and restored later on) and the aeration rate adjusted accordingly, retaining heat in the heap.

In the event of temperatures still being too low to achieve chalcopyrite-leaching, oxygen enriched gas could be substituted for air, in order to further reduce cooling at the base of the heap, increasing the average heap temperature. Offgas from thermophile bioleach plants (those using oxygen) and from electrowinning cells would be useful in this regard.

Small quantities of chloride, naturally present in the ore, or added into the system will enhance the leaching of sulphide minerals.

To maintain a healthy microbial environment the microorganisms must have an adequate supply of nutrients. In tank systems processing concentrates the nutrients are added continuously with the concentrate. In the case of heap leaching though, nutrients in solid form can only be added once, when the ore is stacked. Such nutrients should be specifically designed to release slowly into solution, for the entire duration of the leach cycle. Alternatively the nutrients can



be added with the irrigation solution, although in high heaps in particular, chemistry considerations may make it difficult for nutrients to reach the lower part of the heap. It is also foreseen that nutrients can be added via air addition as an aerosol and/or ammonia gas. Additionally the microorganisms require a source of carbon for cell growth. Carbon can be conveniently supplied by adding carbonates mixed in with the ore heap or adding in carbon dioxide to the aeration supply. The amount of carbon and nutrients added is chosen to maintain high rates of microorganism growth and sulphide oxidation.

Metal can be recovered from solution by means well established in the art, for example by solvent extraction or ion exchange. Gold can be recovered from oxidised gold bearing sulphides by cyanidation.

The invention is further described by way of non-limiting examples with reference to the accompanying drawings, Figures 14 to 16, which respectively illustrate different embodiments of the invention.

#### Example 1 – First Ore to be Leached

Example 1 shows a case where an on-off pad system is used for the heap leaching process. Figure 14 on the accompanying drawings illustrates a layer of granular material, consisting of crushed rock, 1a placed on a pad 2a, which has been equipped with a drainage system 3a as well as an aeration system 4a. The aeration system is fed with ambient air 6a from a variable speed and reversible direction blower 7a. The layer of granular material 1a has a hot solution irrigation system 5a, fed with hot solution 8a from a hot solution source 9a. The layer of granular material 1a then has a layer of ore (the first ore to be leached) 10a placed on top of it. The ore heap 10a has an irrigation system 11a installed, as well as plurality of temperature probes 12a installed over the area of the ore heap 10a in a horizontal grid pattern, which are buried beneath the heap surface at various depths. At least some of the temperature probes 12a are connected to a

measurement and control system 13a. A plurality of oxygen analyser probes 22a, spaced in a similar manner as the temperature probes 12a, are used to measure oxygen levels within the heap 10a and at least some are also linked into the measurement and control system 13a. The initial heap 10a that is to be leached is brought to the take-off temperature by simultaneously feeding ambient air 6a into the layer of granular material 1a using the blower 7a, via the aeration system 4a; as well as hot solution 8a from the hot solution source 9a, via the hot solution irrigation system 5a. The solution leaving the heap 14a can be recycled or accumulated as make-up water as required. The temperature in the ore heap is monitored by means of the temperature probes 12a. Once the ore heap 10a has reached the take-off point, feeding of hot solution 8a is stopped. Ambient air 6a and irrigation solution 15a (usually solvent extraction raffinate) are then fed to the heap. The absolute addition rates of both air 6a and irrigation solution 15a, as well as the ratio between them, are adjusted according to the temperature measured by a plurality of temperature probes 12a (in the horizontal and vertical dimension), as well as the oxygen content of the gas phase in the heap measured by a plurality of analysis probes 22a, using the control system 13a. The PLS solution 16a can be processed using a solvent extraction and electrowinning plant 17a. The raffinate 15a from the plant 17a is fed back to the heaps using a variable speed pump (or other flow controller) 18a. Optionally a continuous or intermittent bleed stream 19a can be taken from the raffinate stream 15a and processed in a plant 20a to remove organics and other toxic elements. The purified stream 21a can then be re-introduced into the system. Optionally additional acid 23a may be added into the solvent extraction raffinate 15a. By the end of the leach cycle, a new ore heap will have been stacked elsewhere and the direction of blower 7a will be reversed. When the heat has been transferred to the new ore heap, as described below, the heap 1a (now leached) can then be removed, to make way for newly stacked ore.

#### Example 1 – Subsequently Leached Ore Procedure

For subsequent ore, we seem much the same procedure as described above, except:

- Warm, moist air sucked from old recently leached ore (in place of ambient air 6a in Figure 14) is used to feed other blowers 7a installed for the new heap 10a.
- The hot solution source, hot solution and the irrigation system are not utilised, the heat in the humid air from an old recently leached ore being used instead.

#### Example 2 – First Ore to be Leached

Example 2 shows a case where a fixed pad system is used for the heap leaching process; the first stage is identical to that of the first stage of Example 1.

Figure 15 on the accompanying drawings illustrates a layer of granular material, consisting of crushed rock, 1c placed on a pad 2c, which has been equipped with a drainage system 3c as well as an aeration system 4c. The aeration system is fed with ambient air 6c from a variable speed blower 7c. The layer of granular material 1c has a hot solution irrigation system 5c, fed with hot solution 8c from a hot solution source 9c. The layer of granular material 1c then has a layer of ore (the first ore to be leached) 10c placed on top of it. The ore heap 10c has an irrigation system 11c installed, as well as plurality of temperature probes 12c installed over the area of the ore heap 10c in a horizontal grid pattern, which are buried beneath the heap surface at various depths. At least some of the temperature probes 12c are connected to a measurement and control system 13c. A plurality of oxygen analyser probes 22c, spaced in a similar manner as the temperature probes 12c, are used to measure oxygen levels within the heap 10c and at least some are also linked into the measurement and control system 13c. The initial heap 10c that is to be leached is brought to the take-off temperature by simultaneously feeding ambient air 6c into the layer of granular material 1c using the blower 7c, via the aeration system 4c; as well as hot

solution 8c from the hot solution source 9c, via the hot solution irrigation system 5c. The solution leaving the heap 14c can be recycled or accumulated as make-up water as required. The temperature in the ore heap is monitored by means of the temperature probes 12c. Once the ore heap 10c has reached the take-off point, feeding of hot solution 8c is stopped. Ambient air 6c and irrigation solution 15c (usually solvent extraction raffinate) are then fed to the heap. The absolute addition rates of both air 6c and irrigation solution 15c, as well as the ratio between them, are adjusted according to the temperature measured by a plurality of temperature probes 12c (in the horizontal and vertical dimension), as well as the oxygen content of the gas phase within the heap, measured by a plurality of analysis probes 22c, using the control system 13c. The PLS solution 16c can be processed using a solvent extraction and electrowinning plant 17c. The raffinate 15c from the plant 17c is fed back to the heaps using a variable speed pump (or other flow controller) 18c. Optionally a continuous or intermittent bleed stream 19c can be taken from the raffinate stream 15c and processed in a plant 20c to remove organics and other toxic elements. The purified stream 21c can then be re-introduced into the system. Optionally additional acid 23c may be added into the solvent extraction raffinate 15c. By the end of the leach cycle both the layer of granular material and ore will, in the meanwhile, be stacked on other areas of the pad, and the process described is repeated, until, eventually, the entire pad area as envisaged has both a layer of granular material and leached ore on top of it. At this point, or possibly a little earlier, fresh ore 50c placed on top of old leached ore as shown in Figure 16. However, leached ore heaps will have considerable enthalpy and such enthalpy can be blown into new ore stacked above it, which is illustrated in the next phase, for subsequently leached ore.

#### Example 2 – Subsequently Leached Ore Procedure

For subsequent ore, we seem much the same procedure as described above except:

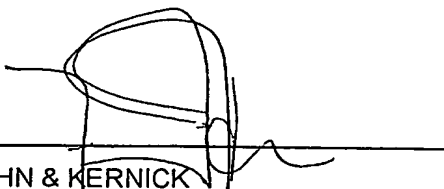
- The variable speed air blower (7c) blows air into the heap as before, but now the air is pushed into the new ore on top of the old heap.
- The hot solution source (9c), hot solution (8c) and the hot solution irrigation system (5c) are not utilised, the heat in the humid air from an old recently leached ore being used instead, as described in the previous bullet point.

New ore is then placed over the entire pad area, with many ore lifts taking place over the pad area during the life of the project.

#### References

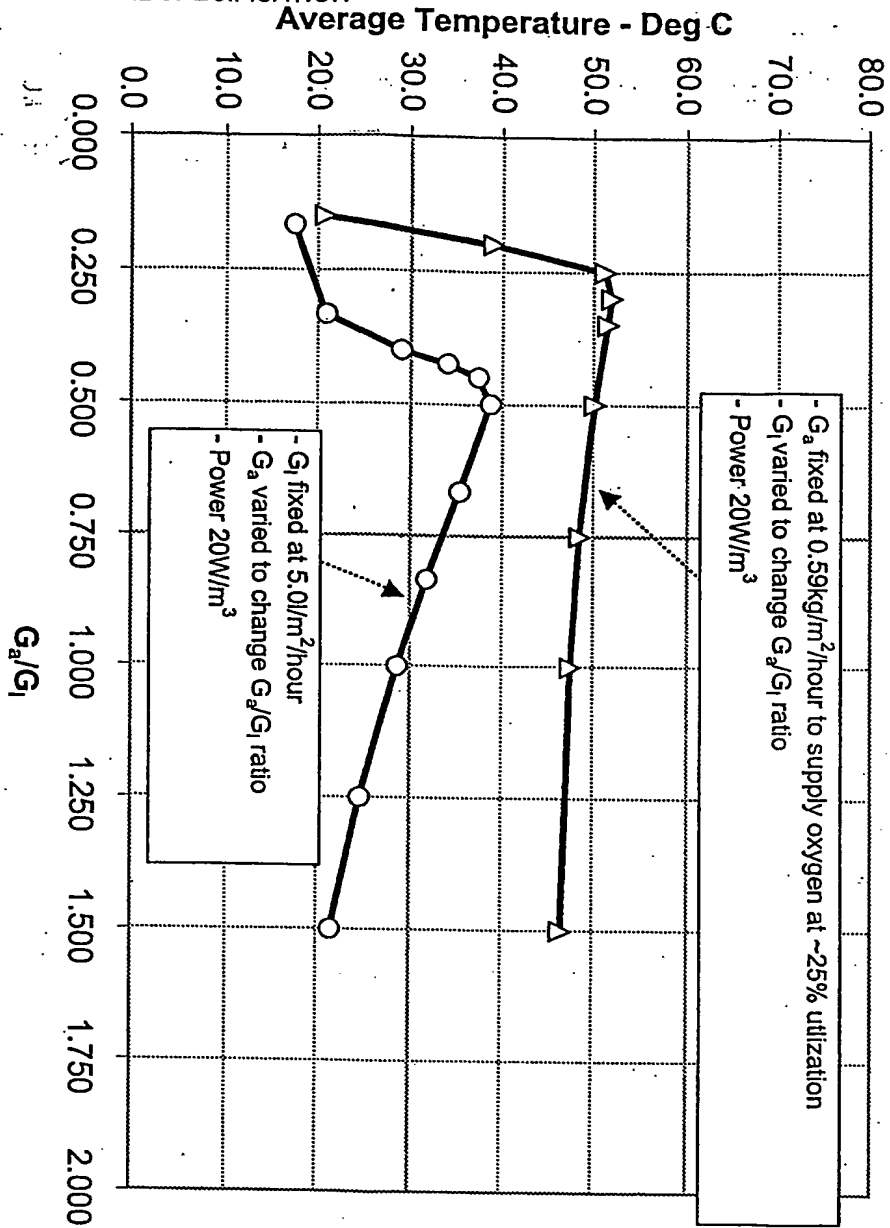
1. Colin Hunter, Titan Resources NL, *BioHEAP™ Leaching of a Primary Nickel-Copper Sulphide Ore*, ALTA Cu-Ni Conference, May 2002, Perth, Western Australia.
2. D.G. Dixon, *Analysis of heat conservation during copper sulphide heap leaching*, Hydrometallurgy, 58 (1) (2000) pp. 27- 41.

DATED THIS 17th DAY OF SEPTEMBER 2002



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Figure 1 - Average Heap Temperature

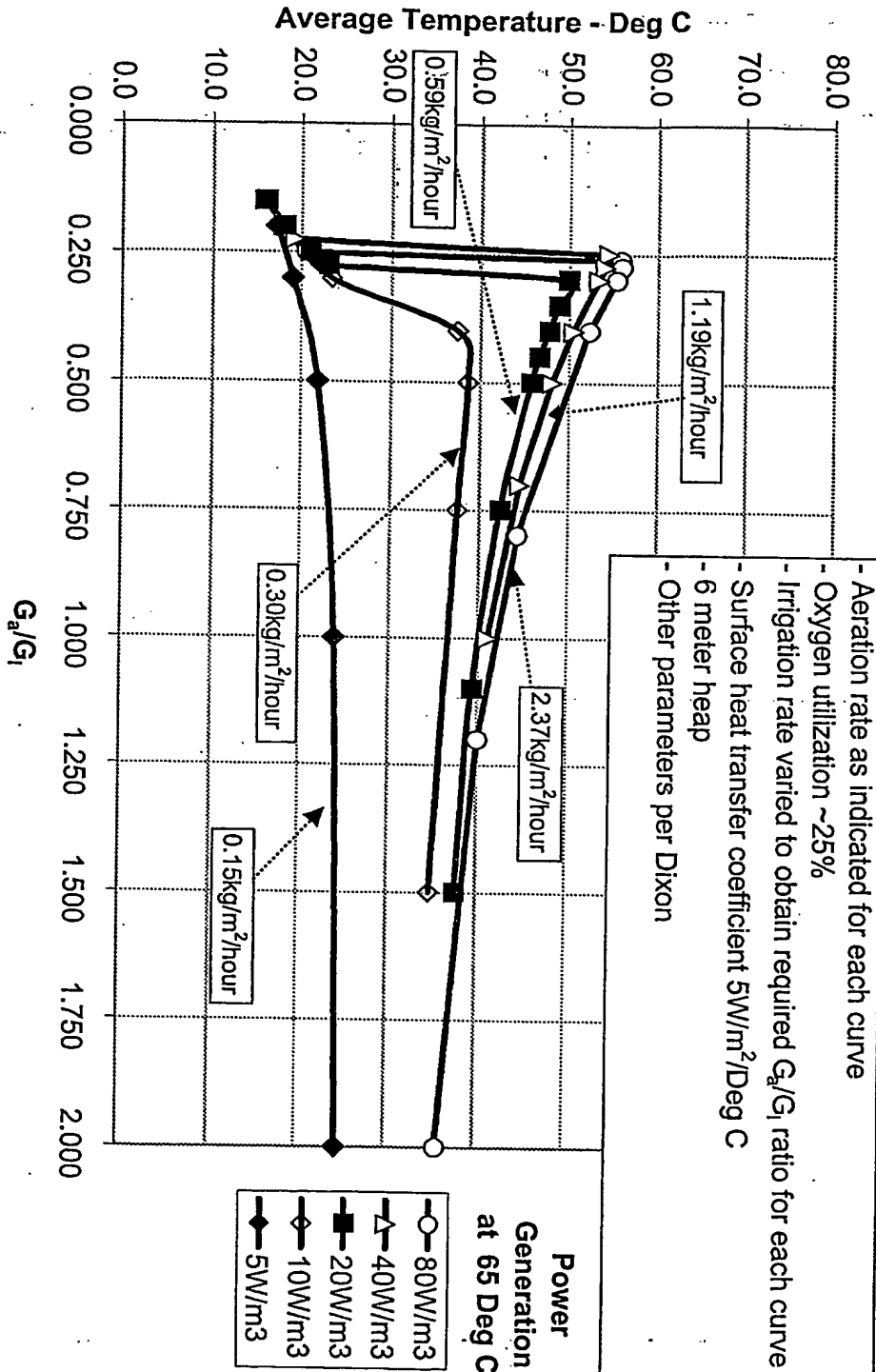


--△-- Applicants approach  
 --○-- Dixon approach

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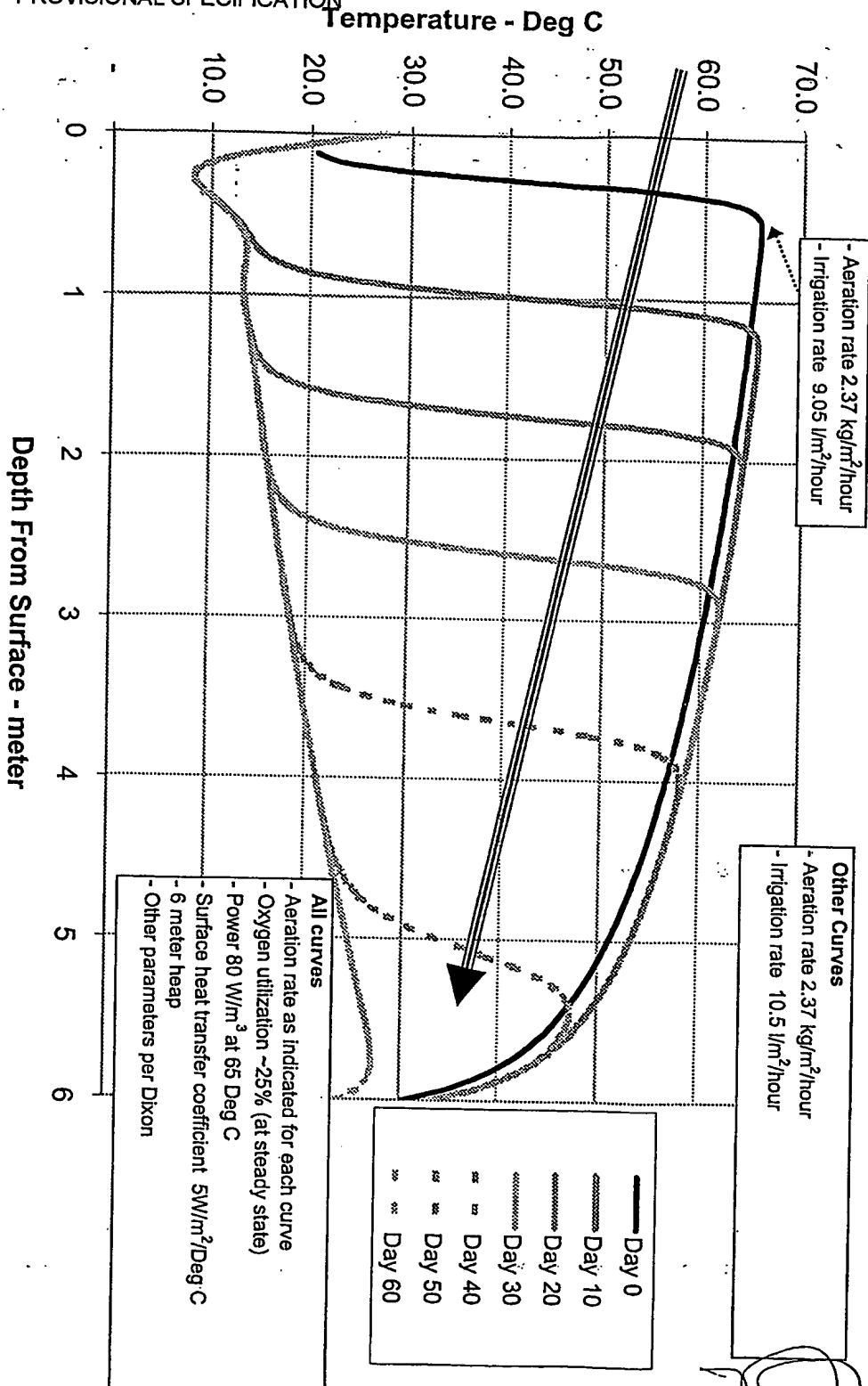
NORTON, Alan Eric; GRUNDWELL, Frank Kenneth  
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Figure 2 – Average Heap Temperature as a Function of Unit Power Generation



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Figure 3 – Collapse of Heap temperature Below Critical  $G_a/G_l$  Ratio



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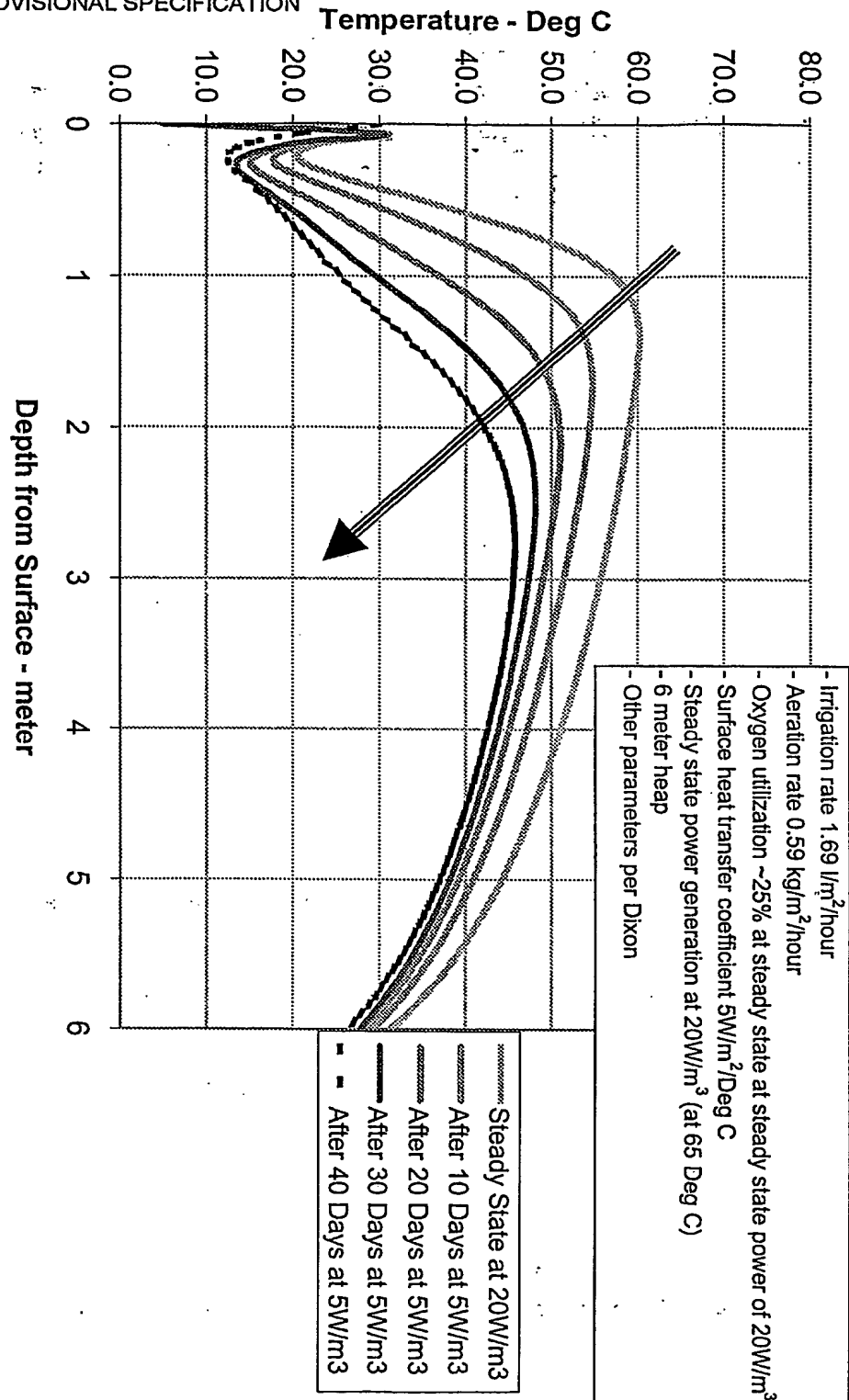


Figure 4a – Effect on Steady State Heap Temperature Profile with a Step Change Down in Power

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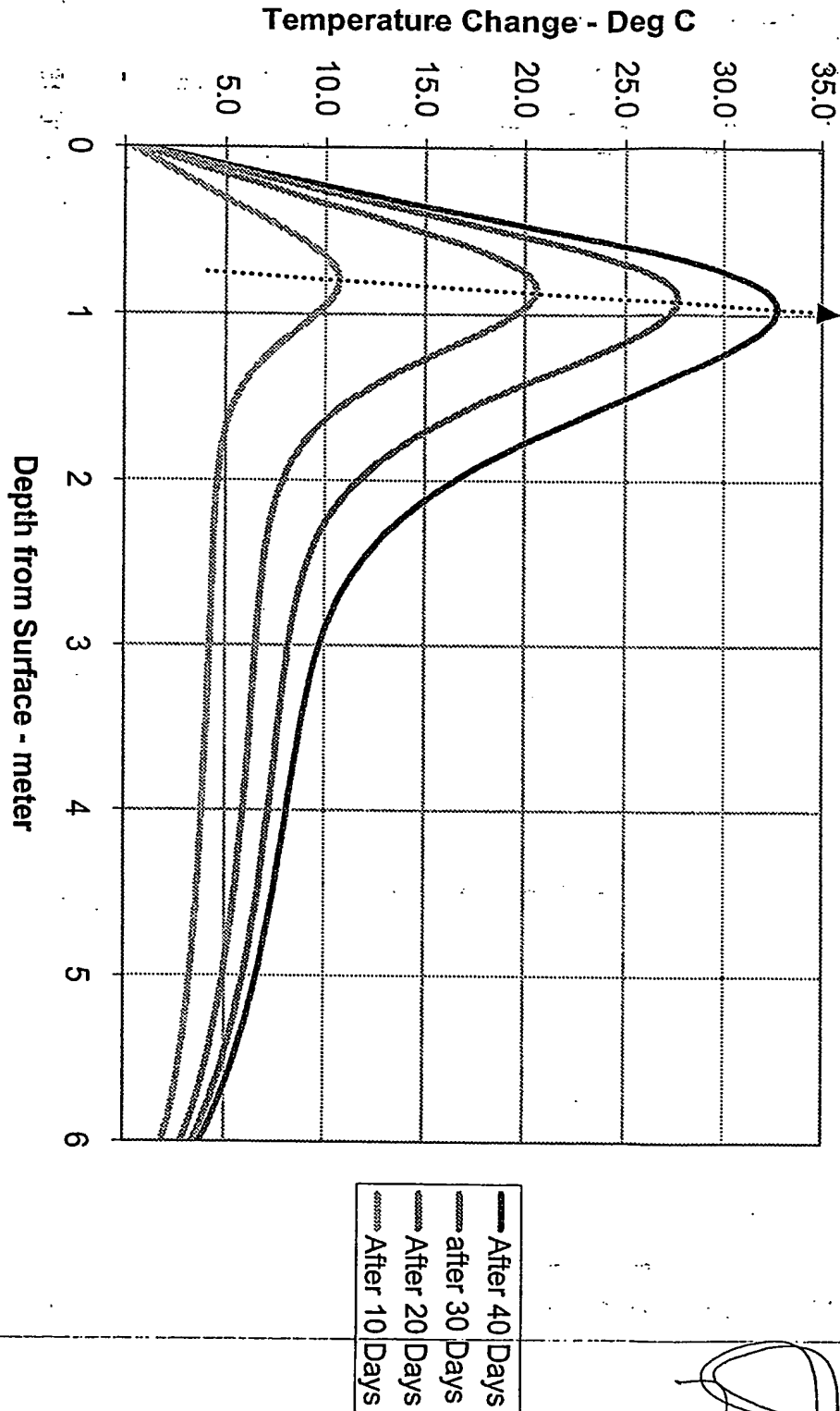


Figure 4b — Change in Temperature at Different Depths After Step Change Down in Power Generation

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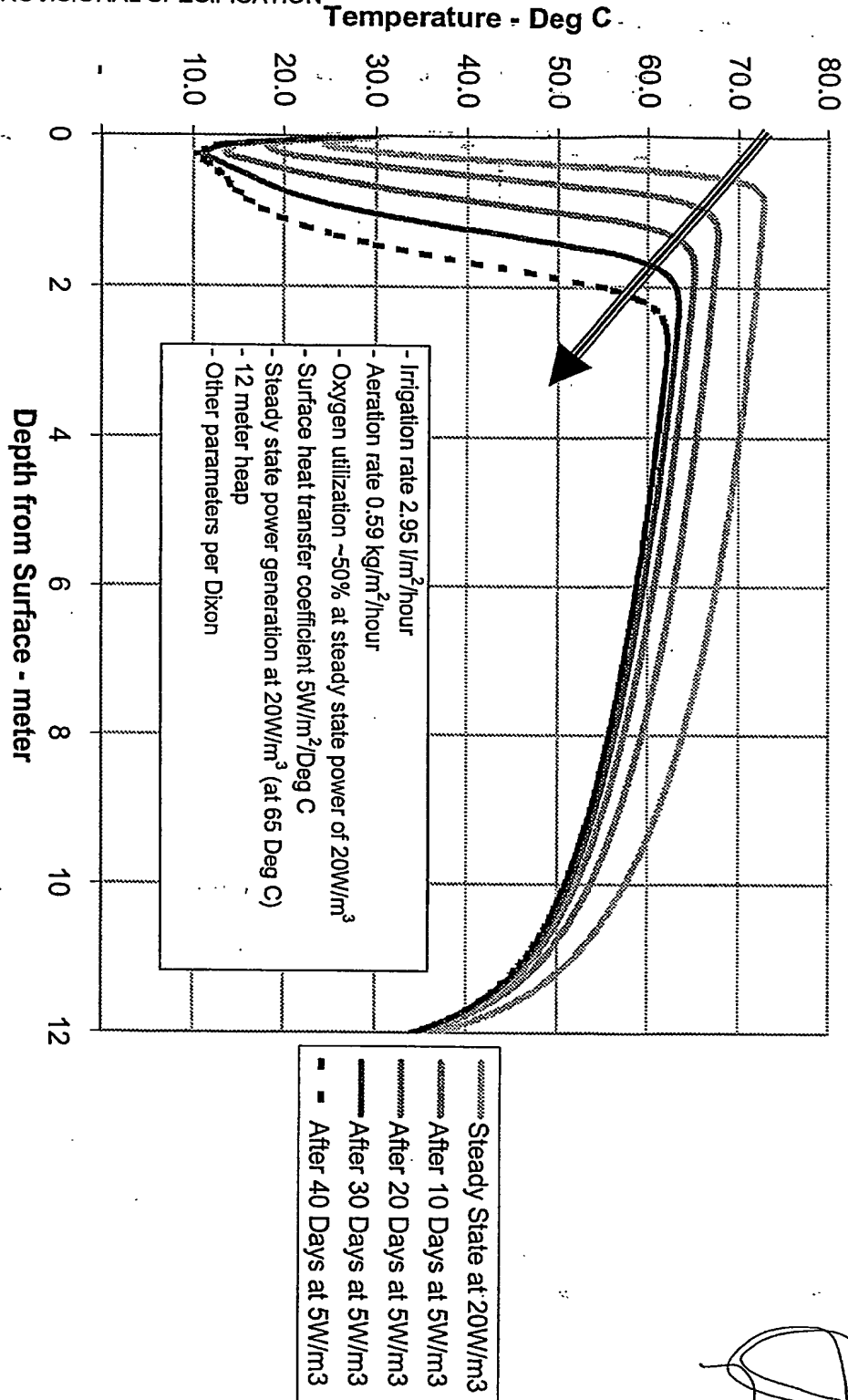


Figure 5a – Effect on Steady State Heap Temperature Profile with a Step Change Down in Power


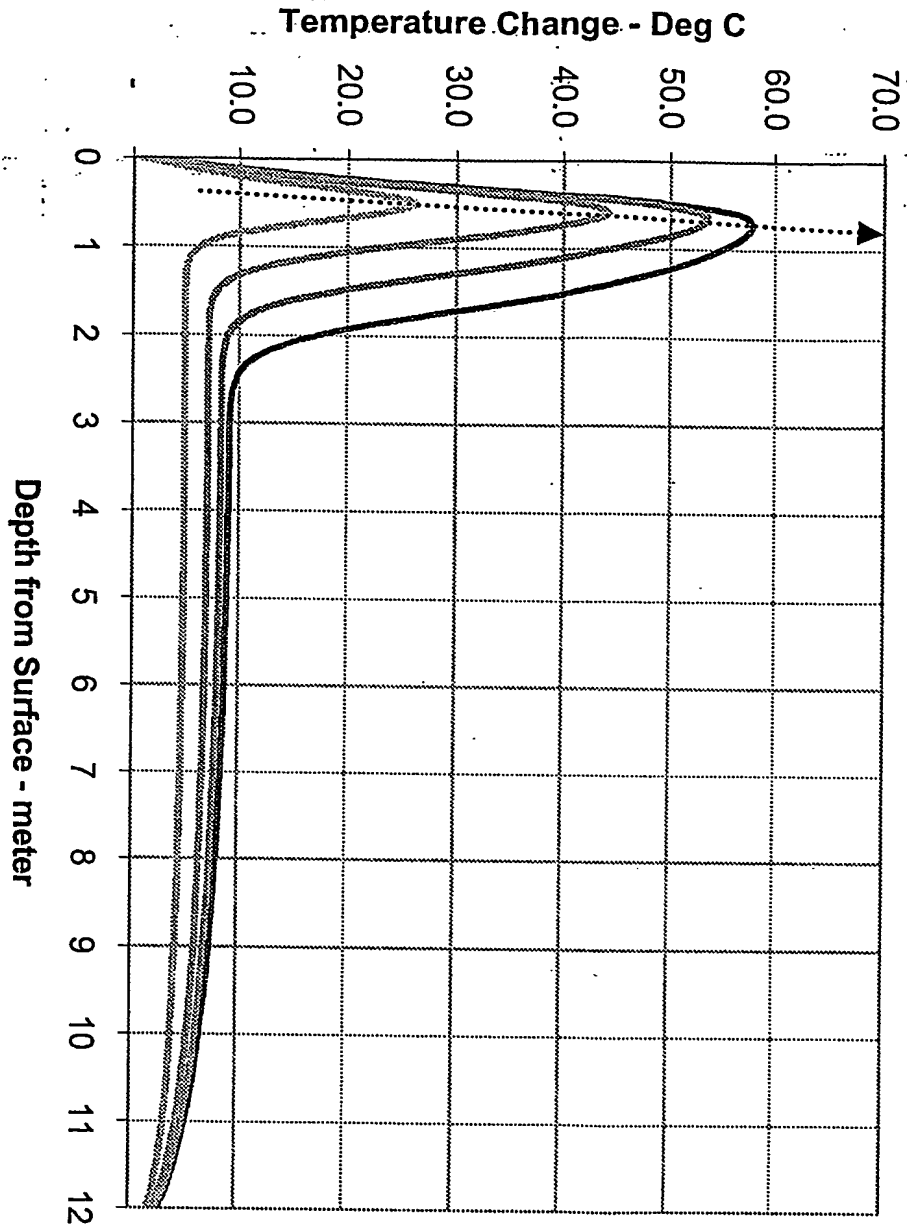
  
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Figure 5b – Change in Temperature at Different Depths After Step Change Down in Power Generation



After 40 Days  
after 30 Days  
After 20 Days  
After 10 Days

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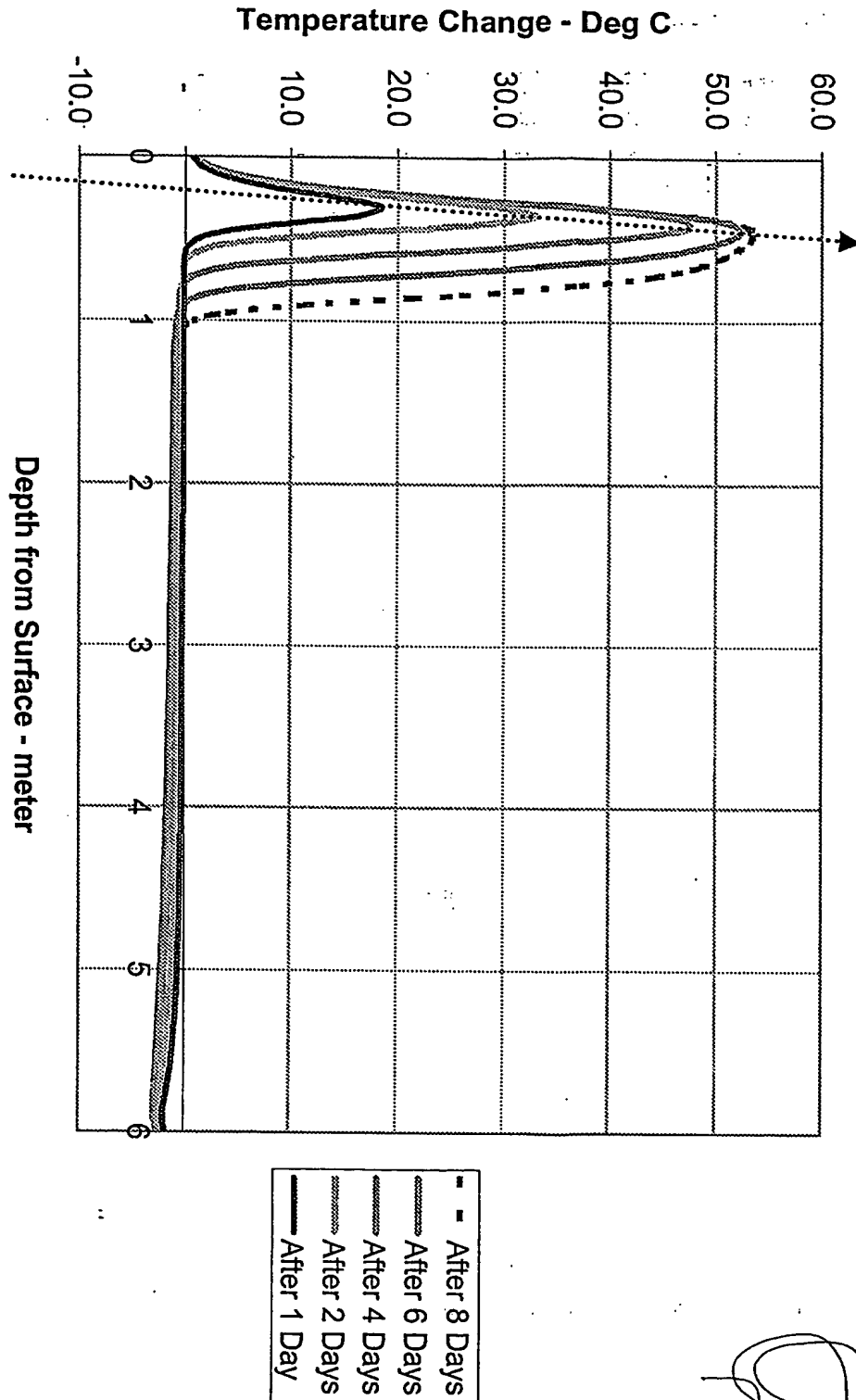


Figure 5c – Change in Temperature at Different Depths After Reduction in  $G_a/G_l$  Ratio Below Optimum


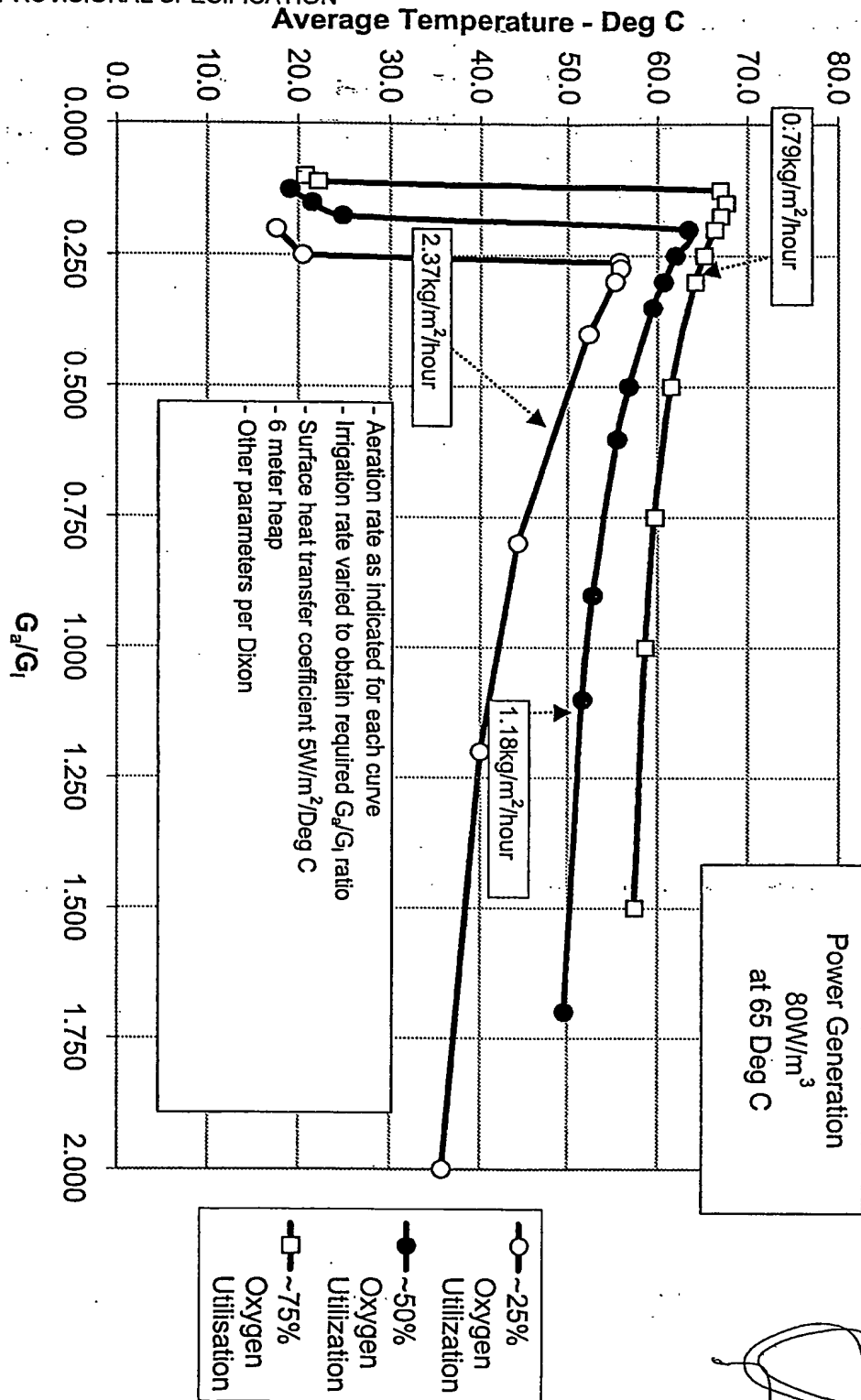
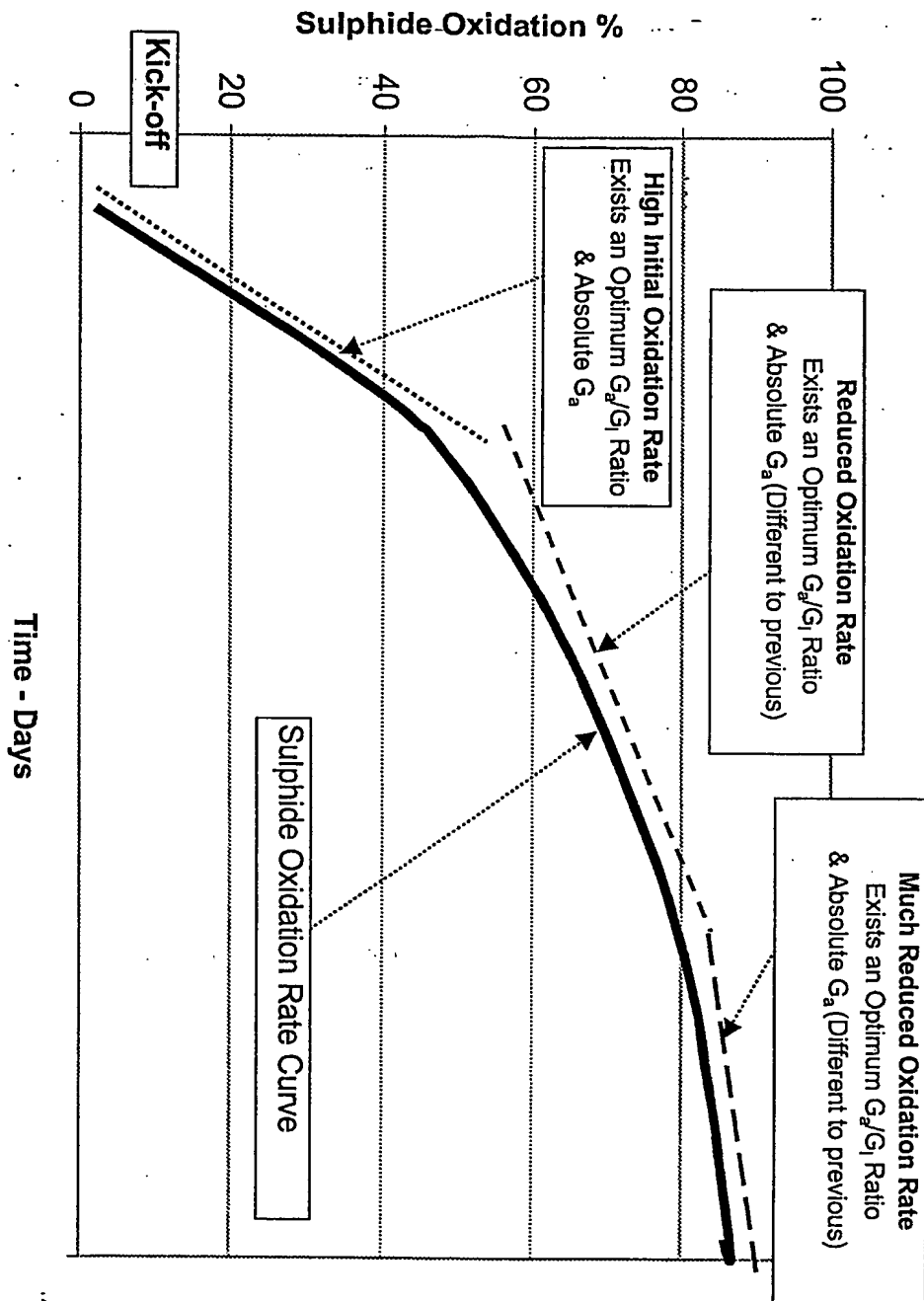
  
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Figure 6 – Average Heap Temperature as a Function of Oxygen Utilization



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Figure 7 – Sulphide Oxidation Rates Vary with Time



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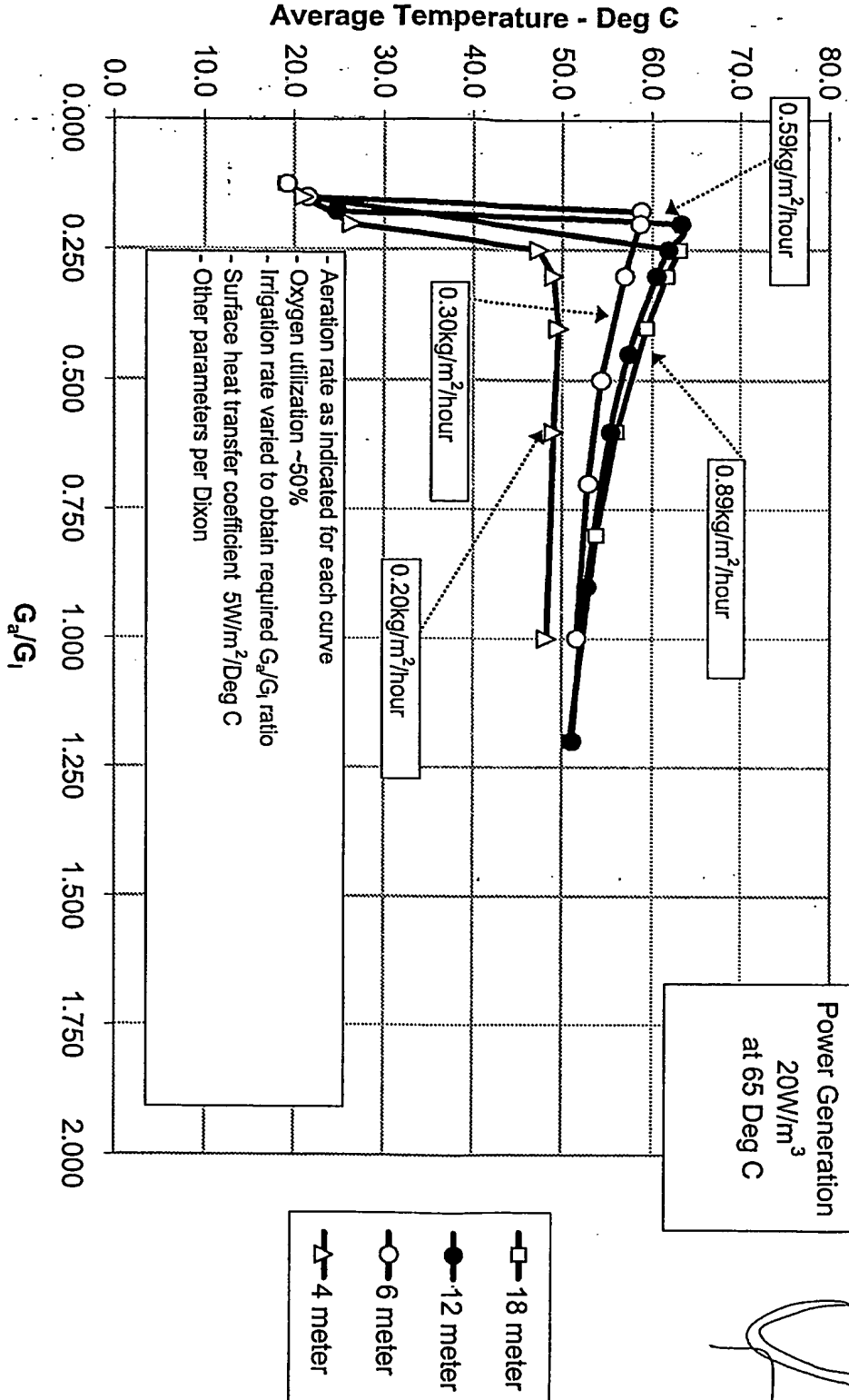
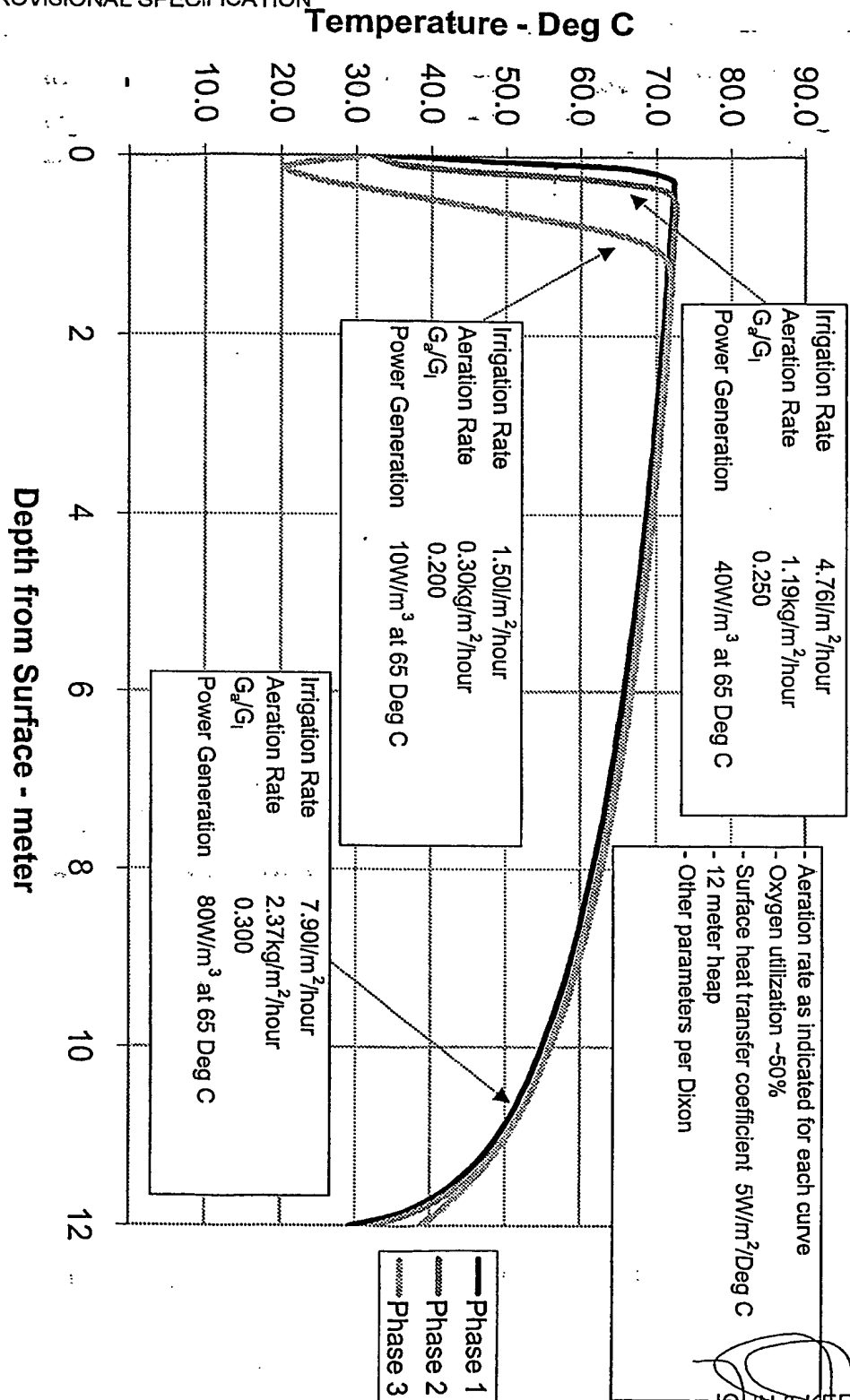


Figure 8 – Effect of Heap Height on Average Heap Temperature

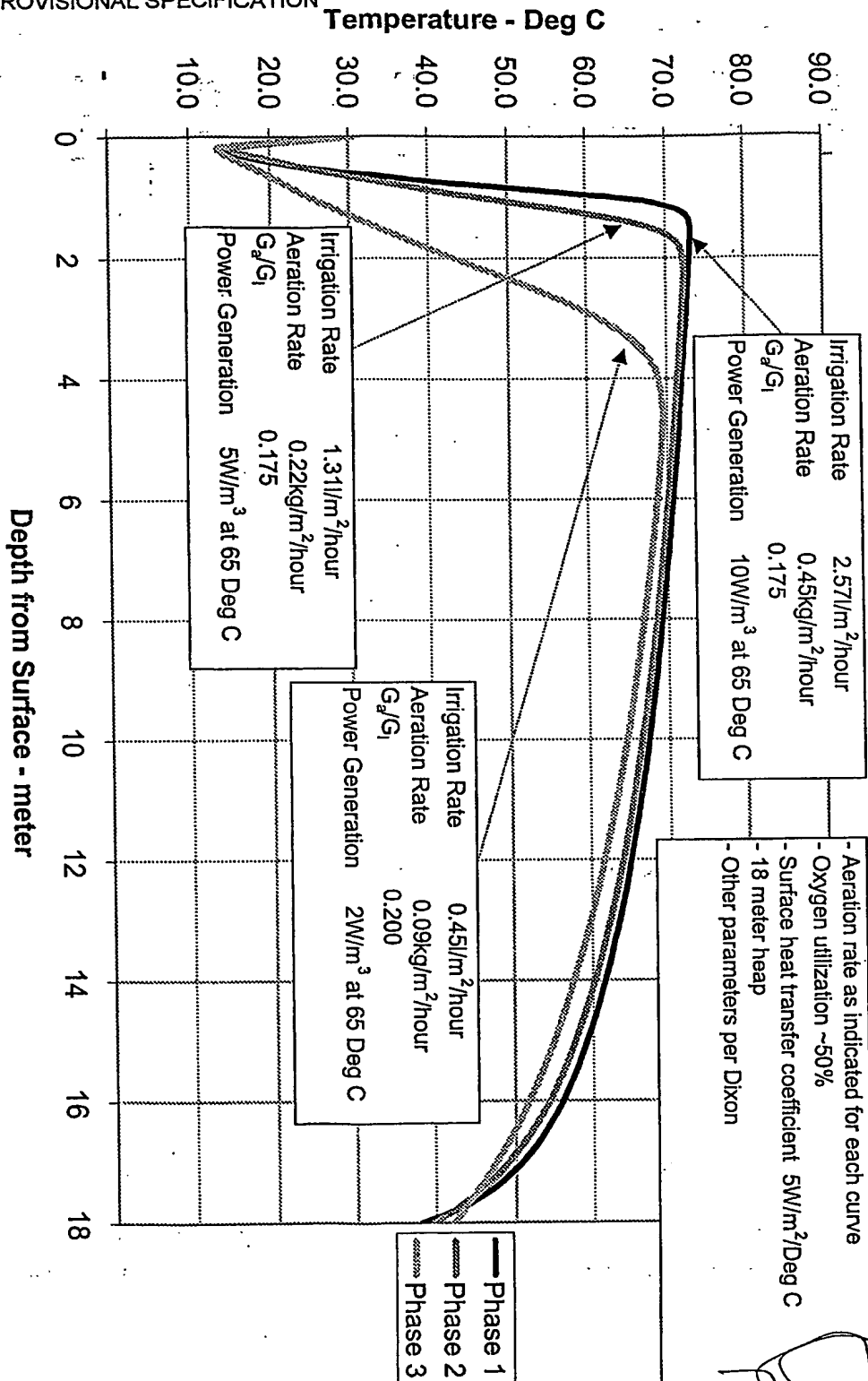
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Figure 9 – Heap Operating Example, Moderate Sulphide Oxidation Rates

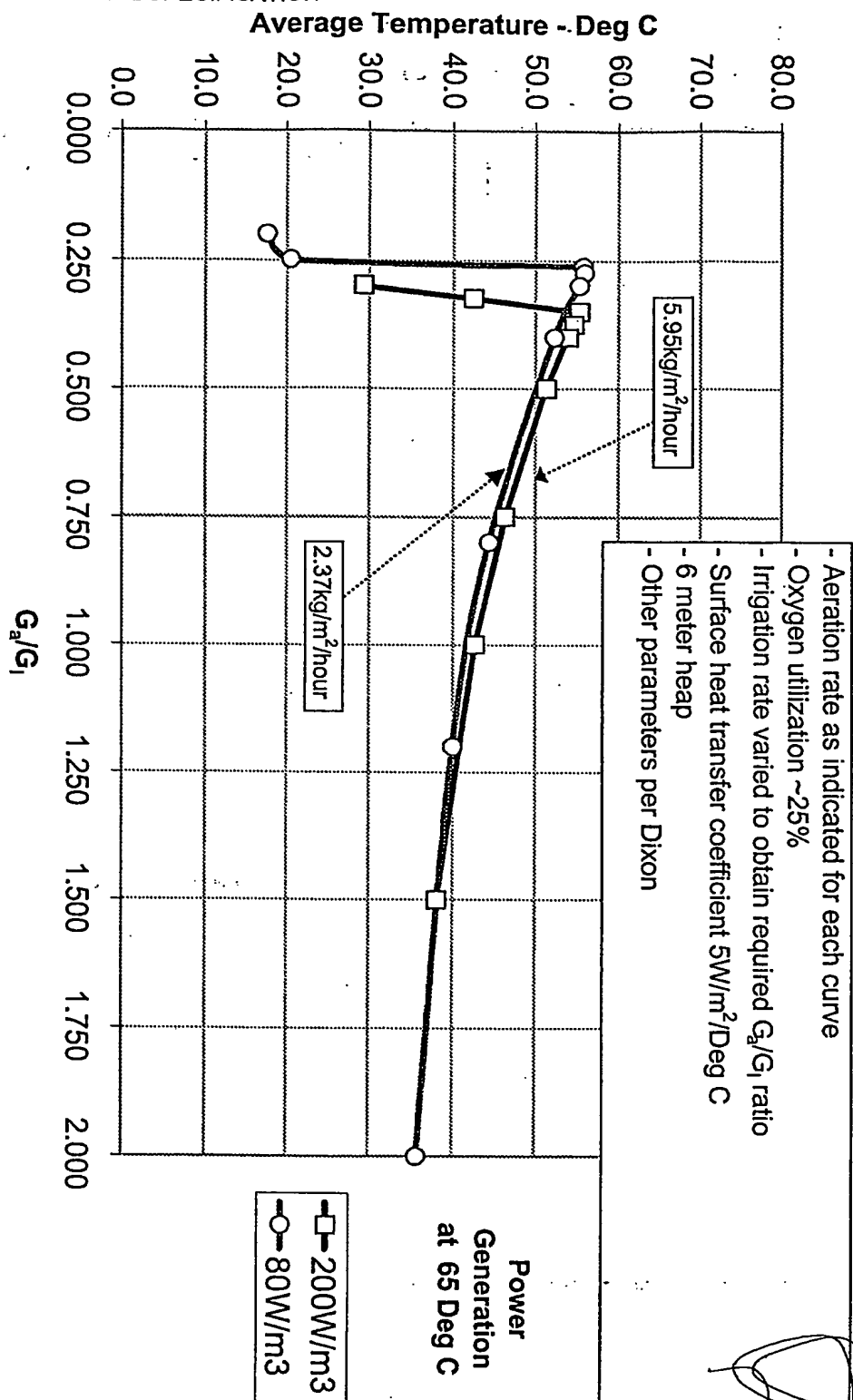


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Figure 10 – Heap Operating Example, Low Sulphide Oxidation Rates



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Figure 11 – Average Heap Temperature, High Sulphide Oxidation Rates

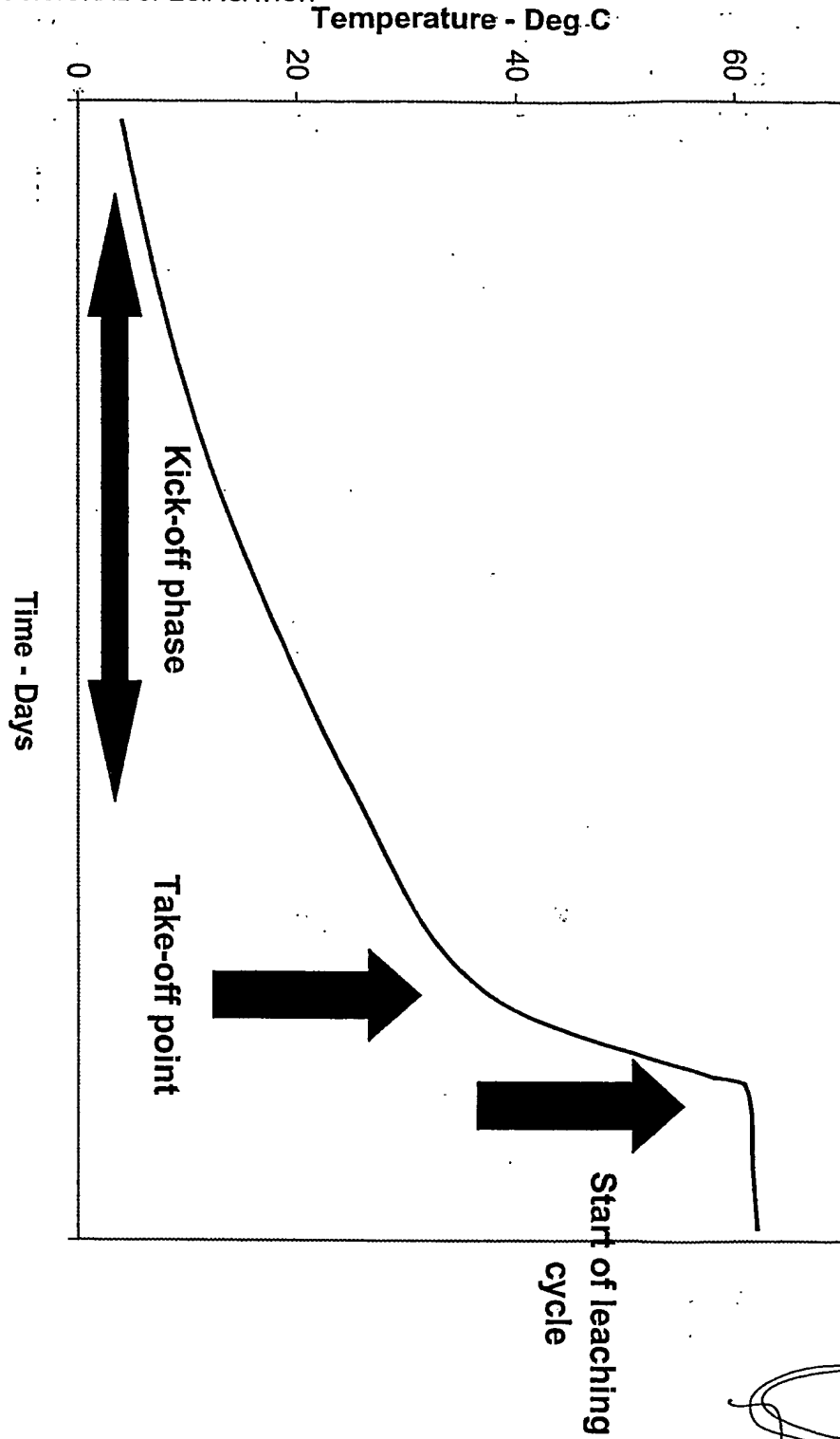


Figure 12 - Kicking Off a Heap - Getting to the "Take-Off" Temperature

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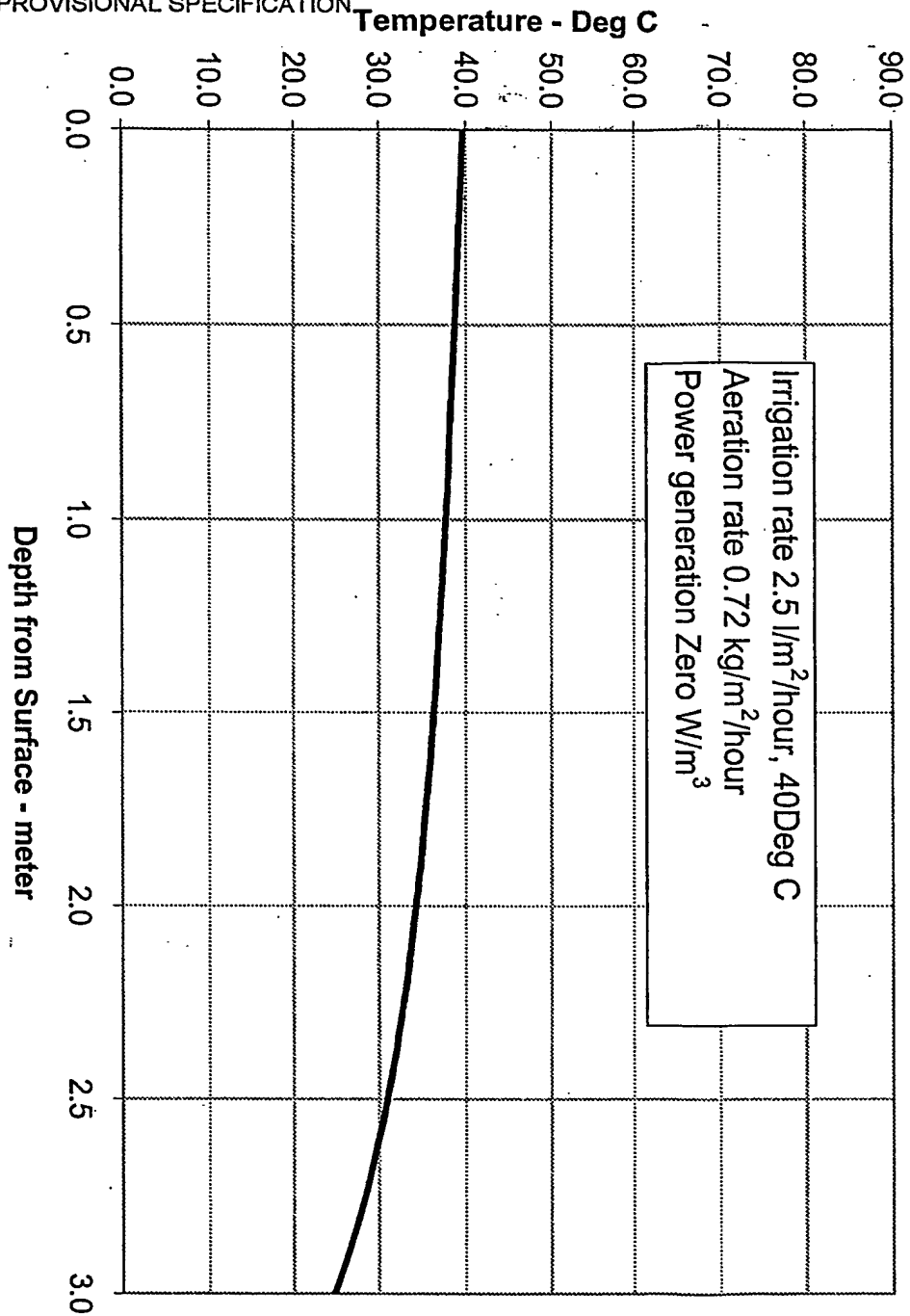

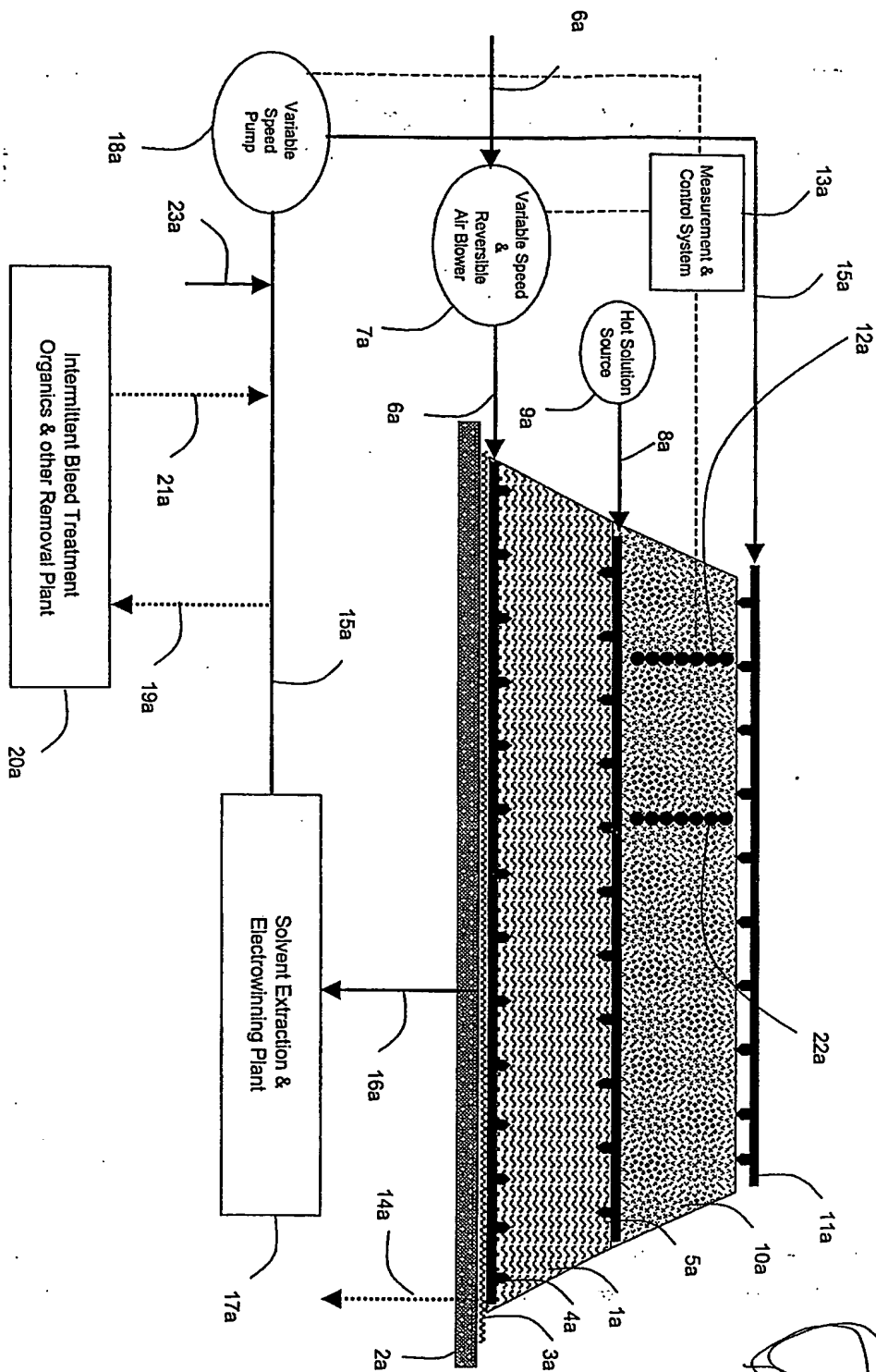


Figure 13 – Kicking Off a Heap - Layer of Granular Material Warming and Humidifying Air

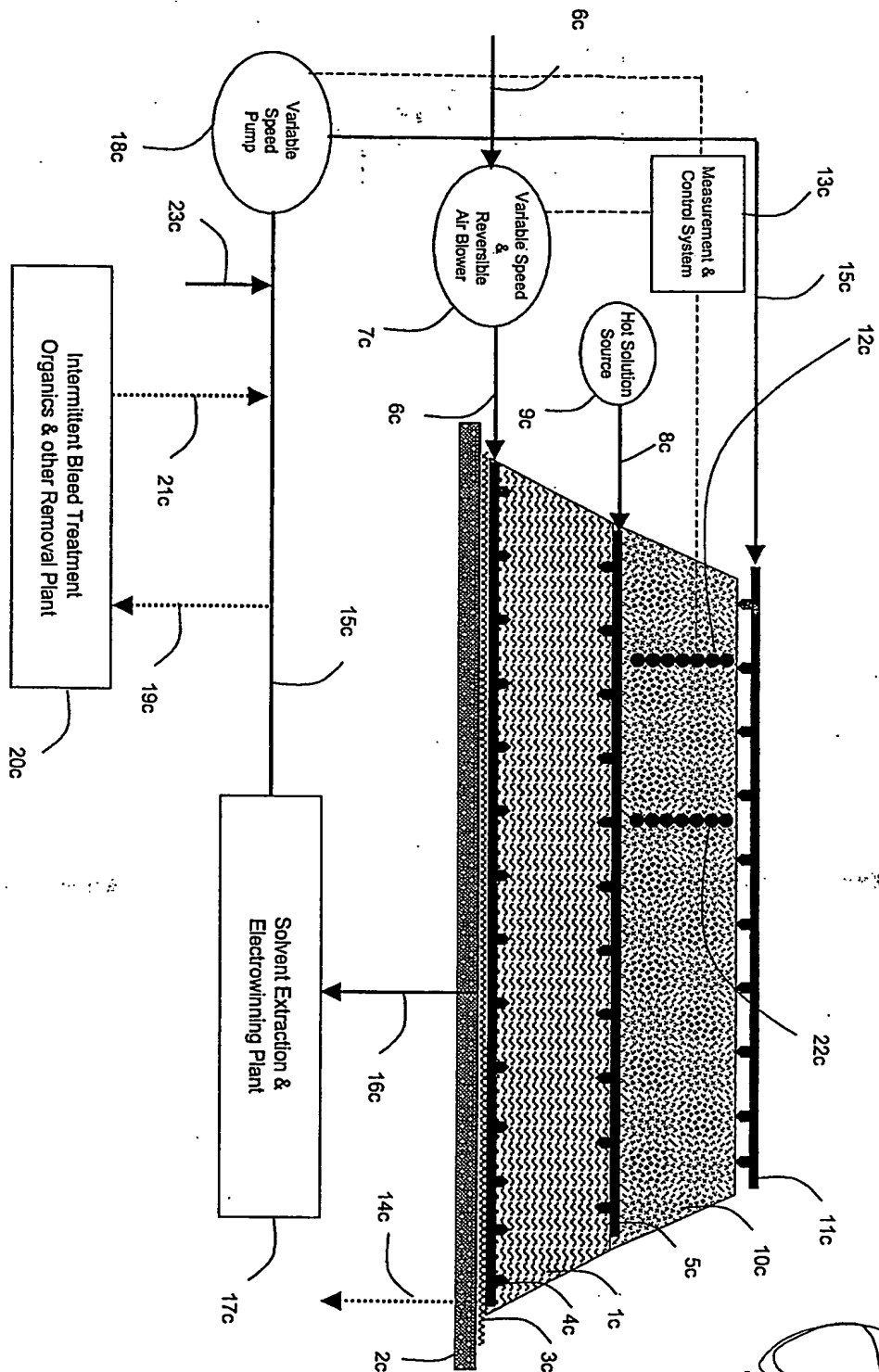
  
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NB: Not to Scale

Figure 14

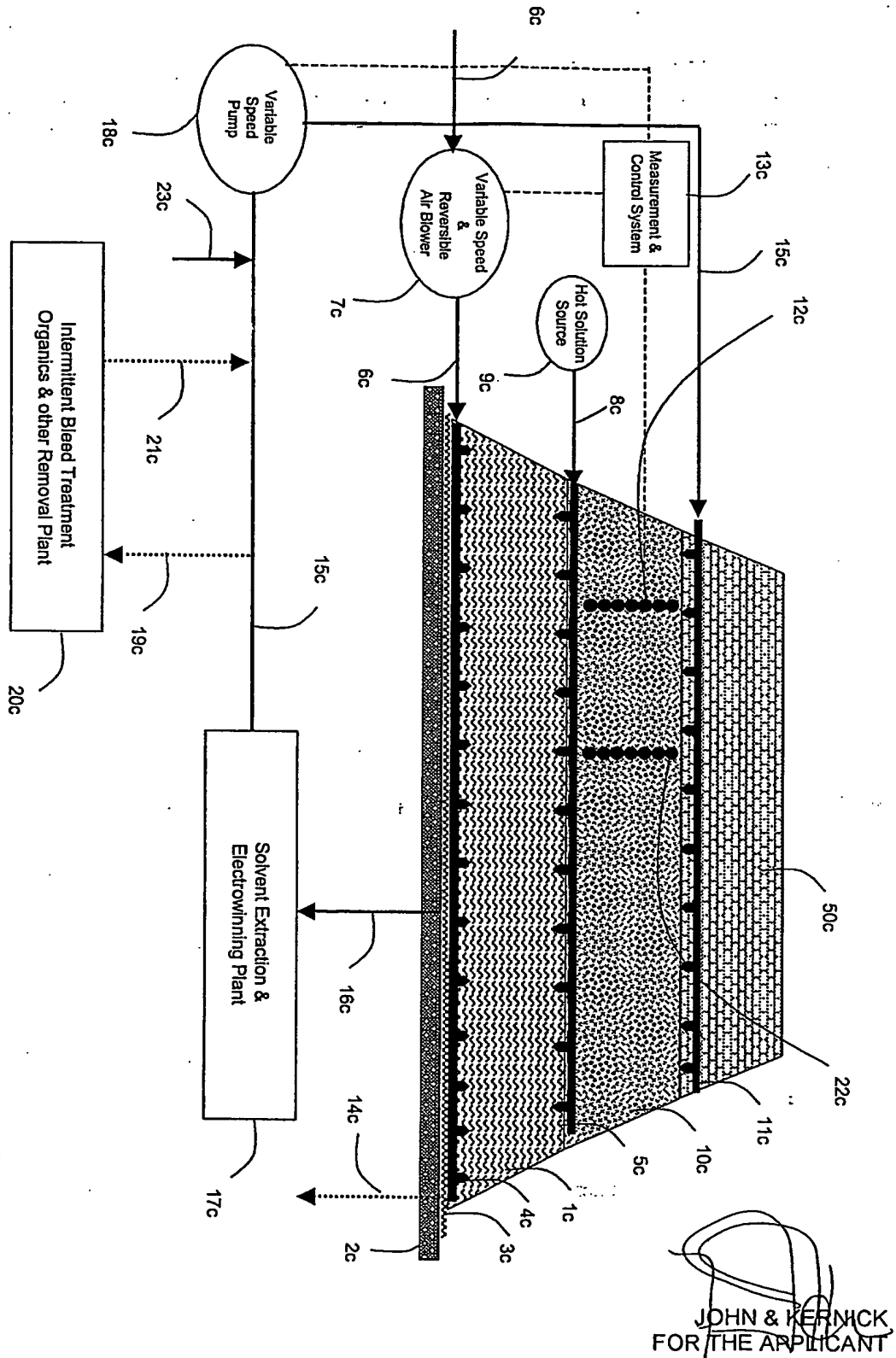
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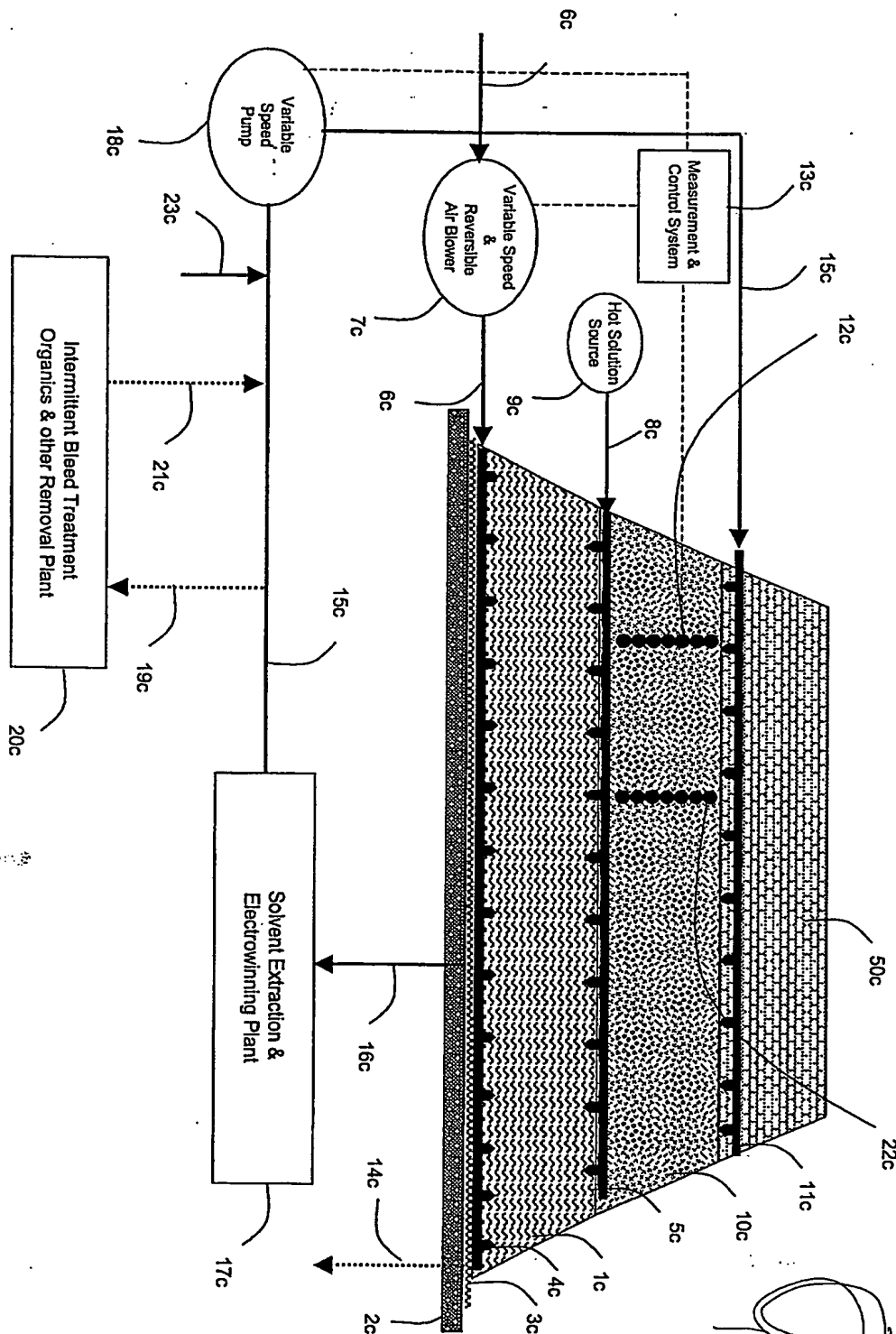
Figure 15

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Figure 16

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